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Hypersonic Research Facilities Study

Volume IV Part 2

Phase III Final Studies

Ground Research Facilities

Prepared Under Contract No. NAS2-5458
by
Advanced Engineering
MCDONNELL AIRCRAFT COMPANY
for
OART - ADVANCED CONCEPTS AND MISSIONS DIVISION
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Moffett Field, California 94035

MCDONNELL AIRCRAFT COMPANY

MCDONNELL DOUGLAS CORPORATION

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FOREWORD

This report presents the results of Phase III of the Hypersonic Research Facilities study performed from 2 January through 26 June 1970 under National Aeronautics and Space Administration Contract NAS2-5458 by McDonnell Aircraft Company, (MCAIR), St. Louis, Missouri, a division of McDonnell Douglas Corporation.

The study was sponsored by the Office of Advanced Research and Technology with Mr. Richard H. Petersen as Study Monitor and Mr. Hubert Drake as alternate Study Monitor.

Mr. Charles J. Pirrello was Manager of the HYFAC project and Mr. Paul A Czysz was Deputy Manager. The study was conducted within MCAIR Advanced Engineering, which is directed by Mr. R. H. Belt, Vice President, Aircraft Engineering. The HYFAC study team was an element of the Advanced Systems Concepts project managed by Mr. Harold D. Altis.

The support of the following companies in the ground facility synthesis is gratefully acknowledged: The Cabot Corporation for extensive design, performance, and operational refinement in carbon combustor concepts; Allis-Chalmers for definition of compressor plant design and equipment requirements. FluiDyne Engineering Company, as a subcontractor on the HYFAC study, contributed significantly to the detailed structural and operational requirements of the flow facility test legs.

The basic task of Phase III was to refine and improve the definition of the facility components associated with those attractive facilities retained from Phase II to provide a base for credible cost estimation, development assessment, and facility design. The Phase III study has been conducted in accordance with the requirements and instructions of NASA RFP A-15109 (HK-81), McDonnell Technical Proposal Report G970, and OART Correspondence received during the Phase III period.

This is Volume IV, Part 2 of the overall HYFAC Report, which is organized as follows:

		NASA CONTRACTOR REPORT NUMBER
Volume I	Summary	CR 114322
Volume II	Phase I Preliminary Studies	
	Part 1 - Research Requirements and Ground Facility Synthesis	CR 114323
	Part 2 - Flight Vehicle Synthesis	CR 114324
Volume III	Phase II Parametric Studies	
	Part 1 - Research Requirements and Ground Facility Synthesis	CR 114325
	Part 2 - Flight Vehicle Synthesis	CR 114326
Volume IV	Phase III Final Studies	
	Part 1 - Flight Research Facilities	CR 114327
	Part 2 - Ground Research Facilities	CR 114328
	Part 3 - Research Requirements Analysis and Ground Facility Potential	CR 114329
Volume V	Limited Rights Data	CR 114330
Volume VI	Operational System Characteristics	CR 114331

ACKNOWLEDGEMENTS

This work was performed by an Aircraft Advanced Engineering study team with Charles J. Pirrello as Study Manager.

The following contributed significantly to the contents of this volume:

P. Czysz	Deputy Study Manager
R. Crook	Flow Facility Design Specialist
W. Cunningham	Non-Flow Facility Design Specialist
C. Hilgarth	Ground Facility Costs Estimator
J. Klingler	Ground Facility Cost Analyst
D. Raines	Facility Systems Analyst

SUMMARY

Airbreathing hypersonic aircraft employing liquid hydrogen fuel have the potential of accomplishing a number of mission requirements in the 1980-2000 time period. For these systems to be either feasible or practical, major advances in the technological state-of-the-art are necessary, therefore, the purpose of Contract NAS2-5458 was to evaluate the research and development requirements for selected potential operational hypersonic aircraft. Based on these requirements, the characteristics and projected costs were defined for a number of facilities which provide the necessary technological increment to attain the confidence level preceding the development of a potential operational hypersonic aircraft. The study is organized into three phases.

- Phase I was a preliminary analysis of a broad spectrum of fifty-four facilities which identified eleven ground research facilities for further refinement in Phase II.
- Phase II involved evaluating the eleven facilities using various tradeoff studies to identify those which could provide the necessary technological increment at minimum costs. Then five facilities identified as warranting further study were carried into Phase III.
- Phase III involved refining the definition of the equipment and components associated with the five facilities to improve the base from which detailed cost estimates and development assessments were made. Improved definition of the facilities would add to the credibility of the facility concepts and their true research capability.

This part of Volume IV presents the results of the analysis of the ground research facilities which refined the description of the more favorable concepts. The significant results obtained are:

1. Gasdynamic facilities which provide a significant increment in present capability are based on existing equipment performance levels.
2. Full scale turbomachinery and ramjet engines can be tested with flight duplicated conditions to Mach numbers near 6 for the potential operational aircraft trajectories.
3. For scramjet engines, only engine modules could be considered for practical experimental facilities. A facility with a high confidence level and significant research capability can be provided at reasonable cost which can test a near full scale engine module for a 600,000 lb (270,000 kg) aircraft.
4. Although it is theoretically possible to provide completely duplicated flight conditions for the entire flight envelope for the potential operational aircraft, material and cooling limitations restrict the degree of simulation for Mach numbers exceeding 10 in continuous facilities.

5. The structures facilities are based on component hardware currently in use, but assembled into a size and complexity that far exceeds current structural facility capability. Major developments must occur in testing technique, not necessarily in hardware performance.

6. There is a generally high confidence that the performance stated for the five facilities refined in Phase III can be achieved. These facilities were judged to provide about a 50% increase in research capability over existing levels. Their cost, compared to the degree of improvement over existing facilities, is very similar to the cost/capability relationship of existing major facilities.

7. A major substudy established the sources, cost, and availability of large amounts of electrical and shaft power.

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LIST OF SYMBOLS

Symbol	Definition
a	acceleration
A	area
AR	aspect ratio
α	angle of attack, ratio of wing span to vehicle length
β	ratio of mean aerodynamic chord to vehicle length, side slip
b	wing span
C_D	drag coefficient
C_{D_O}	zero lift drag coefficient
C	cross sectional area of wind tunnel test section
$\bar{c}$	mean aerodynamic chord
C_R	wing root chord
C_T	wing tip chord
C_1	balance normal force load capacity divided by balance diameter squared
C_L	lift coefficient
C_{L_α}	lift curve slope
$C_{L_{\alpha_O}}$	lift curve slope at zero lift
C_m	pitching moment
d	diameter, balance diameter
D	drag
δ	deflection, or boundary layer thickness
Δ	increment between two values

LIST OF SYMBOLS (Cont)

Symbol	Definition
Δt	test time
ΔV	equivalent velocity requirement
ΔV_i	velocity increment due to i^{th} cause
ΔC_{D_O}	incremental drag at zero lift
e	span efficiency factor
E_c	compressive modulus of elasticity
ϵ	nozzle expansion ratio
F_{tu}	ultimate tensile strength
F_{ty}	yield tensile strength
F	propulsive thrust
f/a	fuel to air weight ratio
γ	ratio of specific heats, flight path angle
g	acceleration due to gravity
g_o	acceleration due to gravity, sea level, 45° geographic latitude = 9.80665 m/sec^2
H	geopotential pressure altitude
h	wind tunnel test section height, vehicle fuselage height
H_2	molecular hydrogen
I_{sp}	specific impulse
K	additional drag factor, ratio of model wing area to wind tunnel test section cross sectional area
K_D	inlet process efficiency
Λ	wing sweep angle
ℓ	moment arm, length
L'	induced drag factor
L	lift, length

LIST OF SYMBOLS (Cont)

Symbol	Definition
L/D	lift to drag ratio
m	mass
M	Mach number, bending moment
$\dot{m}$	mass flow
n_z	flight path normal load factor
η_{KE}	inlet kinetic energy efficiency
N.F.	normal force
n	inlet height-to-width ratio
N_2O_4	nitrogen tetroxide
O_2	molecular oxygen
o/f	oxidizer to fuel weight flow ratio
p	pressure
ϕ	fuel equivalence ratio, ratio of actual fuel flow to stoichiometric fuel flow
θ	angle between shock attachment point and cowl lip
q	dynamic pressure
R	specific gas constant
R_E	mean radius of the earth 6,371,100 m
$\mathcal{R}$	universal gas constant (8.31432 joules/°K mol)
Re	Reynolds number
ρ	density
σ, F_s	stress
S	area
S/R	dimensionless entropy

t	time
T	temperature
T_r	recovery temperature
T_w	wall temperature
V	velocity
Vol	volume
$\dot{w}$	weight flow
x	length
ψ	heading angle, yaw angle
Z	geometric altitude

LIST OF SYMBOLS (Cont)

SUBSCRIPTS

Propulsion Station Designations

0	free stream
c	capture, a fixed reference area on vehicle
cowl	cowl lip
2	engine face
3	engine exit
e	nozzle exit
t	nozzle throat

General

aero	attributable to aerodynamic forces
c	chamber conditions, cruise
cent	attributable to centrifugal forces
D	drag
E	empty
e	engine exit
eff	effective
f	final
F	frontal
i	initial
∞	free stream
G	associated with gravity forces, gross
I	ideal
M	maneuvering

LIST OF SYMBOLS (Cont)

Symbol	Definition
max	maximum
min	minimum
N	net
o	isentropic reservoir conditions, evaluated at zero lift
prop	attributible to propulsion system
p	associated with pressure forces, planform
R	wing root
S	structural
s	vehicle, model stagnation
t	total conditions corresponding to isentropic case
TO	takeoff
TJ	attributable to turbojet propulsion system
SJ	attributable to scramjet propulsion system
t	wing tip
test	associated with test time
w	wing
wet	wetted
vac	associated with vacuum conditions
x	longitudinal direction
y	lateral direction
z	vertical direction

LIST OF ABBREVIATIONS

Abbreviation	Definition
ARC	Ames Research Center
A	ampere
A-h	Ampere-hour
AB	all body
A/D	analog to digital conversion
Alt	altitude
AM	amplitude modulation
Aero 50	Aerozine 50, a 50/50 mixture of UDMH and Hydrazine
bp	boiling point
Btu	British thermal unit
°C	degrees Celcius (centigrade)
c.g.	center of gravity
c.p.	center of pressure
cm	centimeters
CSJ	convertible scramjet
dB	decibel
D/A	digital to analog conversion
diam	diameter
eng	engine
°F	degrees Fahrenheit
FRC	Flight Research Center
ft	feet
fps	feet per second
GE	General Electric Co.

LIST OF ABBREVIATIONS (Cont)

Abbreviation	Definition
hr	hour
Hz	hertz
HF	high frequency
HTO	horizontal takeoff
HYFAC	Hypersonic Research Facilities
ILS	instrument landing system
in.	inch
inst	installed
IRFNA	inhibited red fuming nitric acid
J	joule
JP	jet propulsion fuel
^oK	degrees Kelvin (absolute)
kg	kilogram
L	liquid
lb	pounds, force
LO_2	liquid oxygen
LH_2	liquid hydrogen
lbm	pounds, mass
mi	mile
m	meter
max	maximum
min	minimum
MCAIR	McDonnell Aircraft Company
MDAC (EAST)	McDonnell Douglas Astronautics Company (EAST)

LIST OF ABBREVIATIONS (Cont)

Abbreviation	Definition
nmi	nautical mile
N	newtons
No.	number
OWE	operational weight empty
psi	pounds per square inch
PFRT	Preliminary Flight Rating Test
P&WA	Pratt & Whitney Aircraft
°R	degrees Rankine (absolute)
R&D	research and development
RDT&E	research, development, test, and evaluation
RF	radio frequency
RJ	ramjet
RKT	rocket
RP	rocket propellent
s, sec	seconds
SJ	scramjet
smi	statute mile
TF	turbofan
TIT	turbine inlet temperature
TJ	turbojet
TMC	The Marquard Corporation
TRJ	turboramjet
TOGW	takeoff gross weight
UARL	United Aircraft Research Laboratory

LIST OF ABBREVIATIONS (Cont)

Abbreviation	Definition
UDMH	unsymmetrical dimethyl hydrazine
UHF	ultra high frequency
uninst	uninstalled
VTO	vertical takeoff
V	volt
WB	winged body
W/O	without
wt	weight
W	watt

1. INTRODUCTION

The Phase III results of an investigation of Ground Research Facilities performed as a part of the Hypersonic Research Facilities (HYFAC) Study are presented herein. The primary objectives of the HYFAC Study are to assess the research requirements associated with the development of future (1980-2000) operational hypersonic aircraft and, based on these requirements, provide the NASA with descriptions of a number of desirable facilities with which to accomplish the necessary research. Ground facilities, both new and currently existing, are evaluated to provide an assessment of their capabilities, performance, cost, and acquisition time.

The HYFAC Study was performed in three phases. Phase I involved screening a broad array of fifty-four possible research facility concepts in nine categories of ground facilities, postulated to acquire the research data described in the Research Objectives. Those concepts which could provide a measurable increase in experimental capability over existing facilities were evaluated with respect to the magnitude of their research contribution and acquisition costs. The eleven facility concepts remaining after this screening were those providing a high research value coupled with an experimental capability in excess of the current level. Identification of common hardware which could be shared in common technical areas made it possible to consolidate these into seven integrated facilities which were retained for further study in Phase II. In Phase II, the size, performance and degree of simulation were varied to establish the influence of these characteristics on the acquisition costs. At the conclusion of Phase II, the field of candidate facilities was again narrowed to those facilities which could provide a reasonable increment in research capability, and which could be constructed and operated with a high confidence of achieving the desired performance goals. The five facilities chosen for Phase III refinement were:

(1) integrated polysonic blowdown gas dynamic research facility (GD20)

(2) hypersonic impulse gas dynamic research facility (GD7)

(3) integrated turbomachinery/ramjet engine research facility (E20)

(4) dual-mode ramjet research facility (E9)

(5) integrated structures/fluid systems research facility (S20)

These five ground research concepts are discussed in the following sections. Phase III results pertaining to the Flight Research Facilities are covered in Part I of Volume IV

2. REFINEMENT ANALYSIS AND APPROACH

As a result of the Phase II refinement, the definitions of the experimental working sections of the gas dynamic, engine, and structures research facilities were rather firm. Results of the parametric studies indicated that these elements generally did not represent a major portion of the total acquisition costs and that further attempts to refine the description of these components would yield only small improvements in performance and costs. The support equipment, on the other hand, did represent a major portion of the acquisition costs and further refinements in the descriptions of these items could significantly affect the acquisition and operational costs. In Phase III, the primary emphasis was on obtaining better definitions of the performance and size of the support equipment based on the refined working section definitions. In this manner a more meaningful assessment could be made of the costs and development problems associated with each facility.

The requirements for support systems such as compressors, exhausters, power supplies, steam ejectors and so forth, were described in as much detail as required to identify the system components. Working with manufacturers, suppliers, and designers of this equipment, preliminary plant layouts were made so that reasonably realistic acquisition cost, operating cost, and maintenance cost estimates could be made, as well as valid development assessments. In this manner, these systems, representing major increments of the total facility acquisition costs, would be adequately valuated.

2.1 OBJECTIVE

The primary purpose of the refinement analysis in Phase III was to add credibility to the design concepts and acquisition costs for the support equipment. It was apparent at the end of Phase II that, in most cases, the facility element which provided the experimental capability (i.e., the test leg) was in fact one of the least costly and better defined items. The equipment which supplied the air, water, heating, cooling, and so forth represented the major costs and had the poorer definition. In fact, entire subsystems which were lumped together for gross cost estimates in Phase II appeared to be capable of causing drastic changes in cost upon better definition. With better definition, critical items which would affect development assessments could be identified. Attention paid the performance and size of the test legs during Phase II resulted in a sufficiently good definition so that further refinement would yield only small improvements. Therefore the major effort was aimed at better graphical structural representations of the facilities and more detailed analysis of the equipment requirements in order to more accurately specify the necessary equipment size, performance, and number of elements. This yielded a maximum return by providing a better listing of needed equipment, a better basis for credible cost estimates, a more definitive identification of existing equipment which can provide the necessary capability, a more realistic development assessment, and finally a better basis on which to develop meaningful development schedules.

2.2 DESIGN REFINEMENT GROUND RULES

The refinement ground rules primarily centered on improving detailed technical descriptions of the hardware items which were dominating the acquisition costs so that hardware costs could be minimized without adversely affecting the facility performance. The actual experimental working sections such as the wind tunnel and engine facility test legs were not changed in performance, and only detailed changes were made to the graphic representation of the test leg components to clarify construction methods and improve on the practicality of the fabrication.

In the case of the structures facility, the Phase II equipment specifications were already sufficient, but the actual implementation of the integrated concept required further refinement to provide a viable overall concept.

2.2.1 GAS DYNAMIC RESEARCH FACILITIES - These facility concepts were developed to provide a degree of Mach number-Reynolds number simulation considered necessary to establish the aerodynamics of the full scale aircraft with a high confidence. The Phase I and II analysis showed that a degree of simulation consistent with providing one-fifth of the maximum full scale Reynolds number over the entire Mach number range would probably satisfy this need. These facilities are aerodynamic simulators and do not duplicate the actual temperature, velocity, and density corresponding to flight conditions. As research tools they can provide a significant increase in capability over a wide spectrum of aerodynamic research applicable to:

- o Aerodynamic configuration development
- o Cruise optimization
- o Stability and control
- o Thrust minus drag of propulsion systems
- o Inlet/exhaust nozzle performance
- o Configuration dependent heat transfer.

The performance and size of the test legs were well defined in Phase II. The Phase II analysis did indicate that further refinement was necessary in the compressor/air storage systems and these were the only components for which the detailed descriptions were changed from Phase II values. The primary ground rules for the Phase III refinement were:

o No change in the Reynolds number/Mach number simulation capability or facility size.

o Examination of air storage requirements, run time, air ejector mass flow, and starting durations to minimize air storage volume.

o Examination of conditions on which air storage tank pump-up time is based to minimize compressor size, consistent with productive operation.

o Improved graphical representation of facility so a more realistic structural concept is available to determine material and fabrication costs.

o Consideration of the overall facility in terms of site locations which will accommodate the operational environment produced by the facility.

o Consideration of the operational procedures and safety aspects of the overall facility in terms of the investment required to maintain safe operation, and minimization of damage should a component failure occur.

o Consideration of cost savings possible by integration of candidate facilities into existing facility complexes to utilize existing support equipment.

o Wherever possible, utilization of existing hardware items which have been developed and operationally proven.

2.2.2 ENGINE RESEARCH FACILITIES - These facility concepts were developed to provide a flight duplicated environment for full scale engines (turbomachinery, ramjets) and full scale components (scramjet, convertible scramjet modules). Phase I and II analyses showed that flight duplicated conditions and full scale engine hardware would probably be necessary to accomplish the research associated with advanced engines of the next two decades. The engine research facility concepts developed represent a major increase in capability over the current level. Adaptation of industrial technology, together with a novel approach to scramjet engine testing, resulted in a facility which provides good flight duplication for a larger engine, at less cost than would be obtained using conventional techniques. As research tools, these facilities can provide experimental capability over a wide spectrum of engine research.

- PFRT ratings of engines and components
- Engine-inlet compatibility
  - Time variant/steady state distortion
  - Pressure and thermal distortion sensitivity
- Engine qualification, performance guarantees
- Materials behavior and operational life
- Overhaul and maintenance requirements
- Performance sensitivity to operational, materials, fuels, and design changes.

Since these facilities can provide flight duplicated conditions, aerothermodynamic test legs were designed to be interchangeable with the basic engine cells. These provide additional research capability in the areas of:

- Free jet inlet/engine testing
- Aerothermodynamic research
- Aerothermodynamic configuration refinement

- o Heat transfer research in duplicated conditions using actual aircraft materials

- o Structural research on large sections in flight duplicated environment

- o Materials research

- o Structural thermal control research
  - Surface radiation
  - Structural conductivity
  - Insulation efficiency
  - Active cooling evaluation.

The engine research facilities underwent considerable refinement in the definition of the engine sizes which controlled the required mass flow, and in the detail descriptions of the support equipment which dominated the acquisition costs. From Phase II results it was shown that the actual test leg was a small percentage of the total cost, and that the compressor plant, exhauster plant, coolers, and heaters represented most of the cost of acquiring the facility. A major goal of the Phase III refinement was to obtain sufficiently detailed descriptions of these items to permit realistic cost estimates. The ground rules for the Phase III refinement of the engine research facilities were:

o Phase I and II estimates were based on engine sizes consistent with current study engines. In Phase III these would be projected to 1980-1990 sizes to estimate maximum requirements, for both turbomachinery and scramjet facilities.

o Examination of the size of the free jet leg for the turbomachinery engine facility (E20) to reduce the enormous compressor/exhauster requirements (over 280,000 cubic meters per minute) and yet achieve an acceptable research capability.

o Examination of areas where small sacrifices in research capability might yield major cost savings.

o Further refinement in the description and operation of the heaters and coolers so realistic cost estimates and physical arrangements could be made.

o Determination of whether any significant cost reductions are possible by integration with existing facility complexes.

o Utilization of existing hardware items which have been developed and operationally proven wherever possible.

o Consideration of the over-all facility in terms of location at a site which will accommodate the operational environment produced by the facility.

o Consideration of the operational procedures and safety aspects of the over-all facility, in terms of the investment required to maintain safe operation, and minimization of damage should a component failure occur.

2.2.3 STRUCTURAL RESEARCH FACILITY - This facility concept was developed to provide a simulated local environment for research on large structural sections. In addition, the significant hardware capability required to accomplish this objective can be subdivided to provide research capability for structural components in the areas of:

- o Thermal/mechanical fatigue
- o Acoustic/thermal environments
- o Acoustic/vibration research
- o Fuel system components
- o Fuel tankage research under simulated environments.

For the latter two research areas, a remote hazardous area has been provided where fuel components and loaded fuel tanks can be experimentally evaluated in safety. Although the components comprising this facility are generally the same as those now in use in current structural facilities, the overall size of the structural section and magnitude of thermal input represent about a ten-fold increase in existing capability with full duplicated local environments. This complex represents a major addition to the present structural research capability. The ability of the structural facility to provide the required test data is determined by the amount of test equipment included in the facility and the maximum size of the test article that may be tested. The maximum specimen required to give reliable test results was determined in Phase II to be a major section of the operational aircraft. The facility was designed to duplicate all flight and ground environmental conditions that an operational hypersonic vehicle might experience. The four primary environments simulated in the structural research facility are thermal, mechanical, altitude, and acoustical.

These basic environments may be combined to perform tests under varying environmental and loading conditions. The equipment descriptions developed in Phase II were rather complete in terms of identifying those items necessary to perform the required tests. Phase III refinement was focused on integrating this hardware into a realistic laboratory complex. The primary ground rule controlling the integration was consideration of safety aspects, including fueled structural specimens for cryogenic fuel tank research under simulated flight conditions. The aspects of integration into an existing facility complex were also considered.

2.3 GENERAL COST METHODOLOGY

The guidelines and techniques used to prepare acquisition and operating costs for the ground research facilities retained for Phase III study are presented in this section. All of the facilities were priced by summing the individual costs determined for components comprising the facility complex. The experience and judgement of vendors manufacturing and supplying components was used extensively in establishing a credible base for the cost estimates. Those vendors contributing to this study by providing design, performance, and cost information as well as the sources and references used are identified in Figure 2-1.

2.3.1 ACQUISITION COSTS - Estimating construction work is a process of determining the quantities and costs of material, labor, equipment, and parts required to construct a particular project. The detail and accuracy of any estimate is, by necessity, commensurate with the quality and detail of the written criteria and the drawings which were used for its preparation. The estimate is also dependent on the estimator's knowledge of construction techniques, his judgements regarding complexity of construction, and his fund of information about materials, labor, equipment, parts, erection techniques, and installation methods. A resume of the cost estimating process for ground research facilities is presented in Figure 2-2. While some factors may change for a specific facility, the process shown is representative of the estimating procedure.

The estimates prepared for this report are classified as budgetary. The estimator has, therefore, emphasized determining the costs associated with those items having the greatest effect on overall facility cost and has given somewhat less attention to those items having a small influence on the overall cost. The contingency factor associated with this type of estimate is 10% which covers elements that might not be apparent in the simplified descriptions used. Considering the quantity and detail of the written criteria for those facilities retained through Phase III and the detail of the conceptual drawings, it is felt that the estimates developed for each facility represent a factual basis for any evaluations or trade-offs that might be influenced by cost factors.

FIGURE 2–1

FACILITY COMPONENT – COST ESTIMATE BASE MATRIX FOR GROUND RESEARCH FACILITIES

Hazardous Test Area	Cryogenic Supplies	Boilers	LO_2 Alcohol Altitude Simulation System	Miscellaneous Test Equipment	Hydraulic System	Liquid Gas Converters	Instrumentation and Data Acquisition Sys	Automatic Control System	Substation	Model Assembly Building	Lab and Office Building	Test Section Shelter	Intake Towers	Dehumidification Coolers	Control Valve	Piping (To Test Leg)	Refrigerator	Building	Refrigeration Plant	Control Valve	Piping (to Test Leg)	Storage Tanks	Air Storage	Control Valve	Piping (To Exhaust Muffler)	Exhauster	Building	Exhauster Plant	Control Valve	Piping (To Test Leg)	Storage Tanks	Nitrogen Gas Storage	Control Valves	Piping (To Storage Tanks)	Compressor	Building	Compressor Plant	Oil Gas Fired Heat Exchanger	Carbon Monoxide Combustor	Thermal Insulation	Zirconia Brick	Alumina Brick	Premix Burners	Heater Shell and Foundation	Cold Air Pipe	Zirconia Storage Heater	Control Valve	Hot Air Pipe	Heater Tubes (Columbium Matrix)	Heater Tubes (Steel Matrix)	Thermal Insulation	Induction Coils	Shaded Pole Structure	Heater Shell and Foundation	Cold Air Pipe	Induction Heater	Graphite Resistance Heater	Heater Reservoir Chamber	Gas Piston Driver	Water Cooled Diffuser Spools	Mach 12 Nozzle and Diffuser	Mach 9 Nozzle and Diffuser	Mach 6 Nozzle and Diffuser	Thermostructure Test Cabin	[illegible]
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TIES

Cost Estimate Base	Facility	Heater Tubes (Steel Matrix)	Thermal Insulation	Induction Coils	Shaded Pole Structure	Heater Shell and Foundation	Cold Air Pipe	Induction Heater	Graphite Resistance Heater	Heater Reservoir Chamber	Gas Piston Driver	Water Cooled Diffuser Spools	Mach 12 Nozzle and Diffuser	Mach 9 Nozzle and Diffuser	Mach 6 Nozzle and Diffuser	Thermostructure Test Cabin	Thermostructure Test Accessories	Muffler	Water Cooled Diffuser Spools	Adjustable Diffuser and Mechanism	Fixed Diffuser Section	Porous Walls	Water Spray Assemblies
Richardson Eng. Serv. Est. Manual		●			●	●	●			●		●	●	●	●	●		●	●	●	●	●	●
City of El Segundo Resolution 231																		●					
MCAIR Reports																							
MCAIR Budgets									●														
MDAC-ED Reports																							
MDAC-ED Budgets																			●				
Cleveland Coppersmith Co.				●																			
Ajax Magnethermic Co.				●																			
Coen Co.																							
Nooter Corp.												●								●	●		
Arnold Engineering Dev. Center																							
Norton Company			●																				
Zirconia Corp. of America			●																				
Harbison-Walker Refractories Co.			●																				
Cabot Corporation																							
Fansteel Corp.																							
Allis Chalmers Mfg. Co.																							
E.B.V. Systems, Inc.																							
PDM Steel Co.																							
Vilter Manufacturing Co.																							
Air Reduction Co.																							
Process and Chemical Equipment Co.																							
Cleaver Brooks																							
Jacksonville, Ill. Water and Light Dept.																							
General Electric Co.																							
Pratt and Whitney Aircraft																							
Combustion Engineering																							
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F.C. Brown and Co.																							
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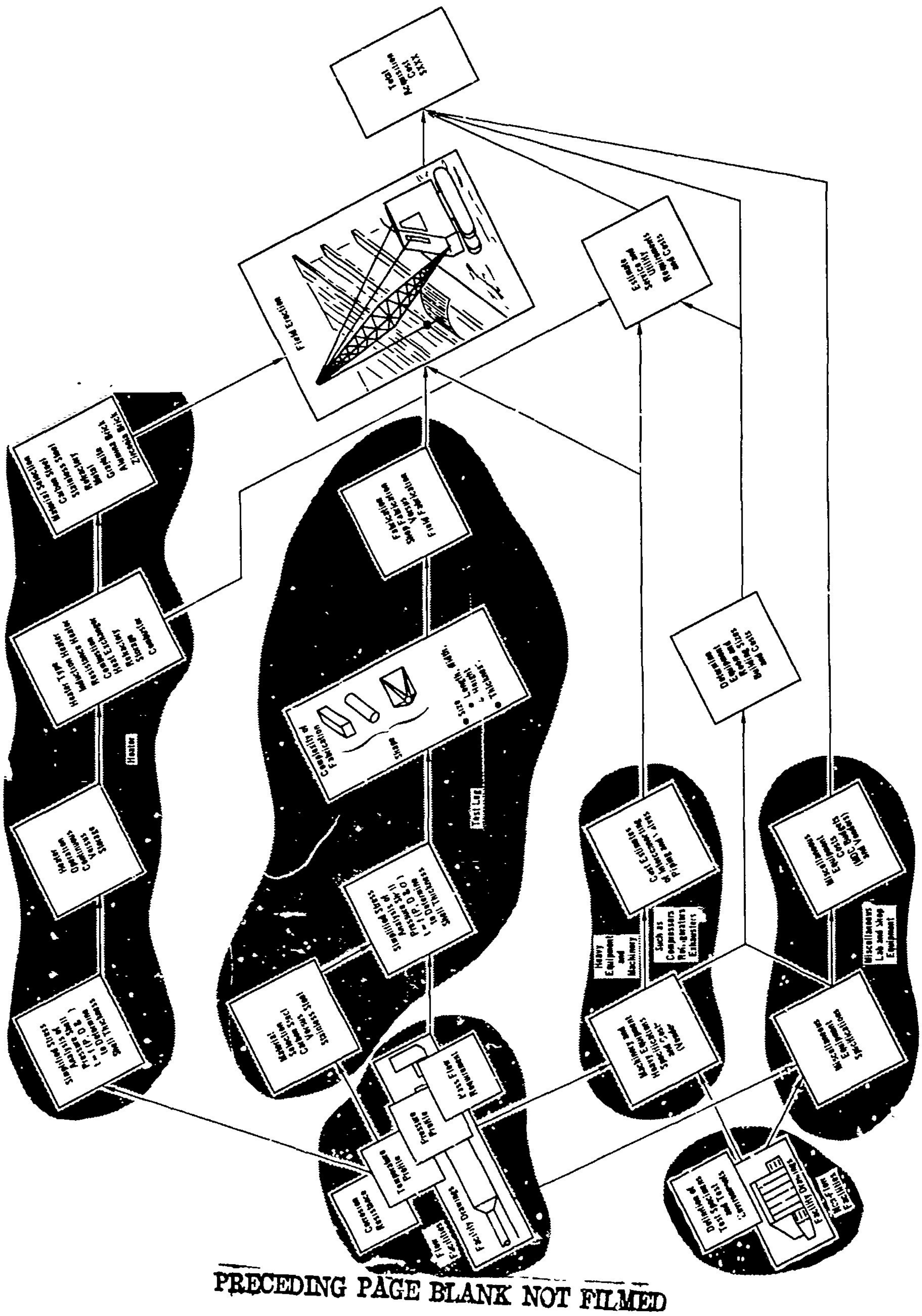
NASA Reports																							
NASA Lewis				●	●	●		●															
Structural Facility	S 20																						
Mach 8 to 10 Leg	GD 7								●	●								●			●		
Mach 10 to 13 Leg									●	●								●			●		
Common to Both Legs																							
Trisonic Leg	GD 20																	●		●			
Hypersonic Leg		●	●	●	●	●	●											●		●			
Common to Both Legs																							
Hybrid Engine Facility	E 9	●	●	●	●	●	●					●	●	●	●	●		●	●				
Direct Connect Leg	E 20																						●
Freejet Leg																				●		●	
Common to Both Legs			●	●	●	●	●											●					

Cost Estimate Base	Facility	Ejector	Mixed Section	Barometric Sump	Articulated Test Stand	Thrust Stand	Scramjet Test Module	Model Support System	Test Cabin (Including Schlieren)	Supersonic Test Cart	Transonic Test Cart	Turbofan Test Nozzle	Turbojet Test Nozzle	Turboramjet Test Nozzle	Fixed Contour Nozzles	Flexible Plate Nozzles	Stilling Chamber Screens	Flow Spreader	Pressure Shell	Venturi	Cold Air Inlet Pipes	Footings and Foundations	Test Leg
Richardson Eng. Serv. Est. Manual		●	●	●	●	●	●		●			●	●	●	●	●	●	●	●	●	●	●	
City of El Segundo Resolution 231																							
MCAIR Reports								●	●														
MCAIR Budgets																							
MDAC-ED Reports																							
MDAC-ED Budgets																							
Cleveland Coppersmith Co.																							
Ajax Magnethermic Co.																							
Coen Co.																							
Nooter Corp.																●		●	●				
Arnold Engineering Dev. Center										●	●												
Norton Company																							
Zirconia Corp. of America																							
Harbison-Walker Refractories Co.																							
Cabot Corporation																							
Fansteel Corp.																							
Allis Chalmers Mfg. Co.																							
E.B.V. Systems, Inc.																							
PDM Steel Co.																							
Vilter Manufacturing Co.																							
Air Reduction Co.																							
Process and Chemical Equipment Co.																							
Cleaver Brooks																							
Jacksonville, Ill. Water and Light Dept.																							
General Electric Co.																							
Pratt and Whitney Aircraft																							
Combustion Engineering																							
Ingersoll-Rand																							
F.C. Brown and Co.																							
Linde Division of Union Carbide																							
NASA Reports																							
NASA Lewis																							
Structural Facility	S 20																						
Mach 8 to 10 Leg	GD 7	●	●					●	●						●							●	
Mach 10 to 13 Leg		●	●					●	●						●							●	
Common to Both Legs																							
Trisonic Leg	GD 20	●								●	●					●	●	●	●			●	
Hypersonic Leg		●						●	●							●	●	●	●	●	●	●	
Common to Both Legs																							
Hybrid Engine Facility	E 9						●															●	
Direct Connect Leg	E 20	●		●		●							●	●	●			●	●			●	
Freejet Leg				●	●											●		●	●			●	
Common to Both Legs																							

FOLDOUT FRAME 2

FIGURE 2-2
THE GROUND RESEARCH FACILITY COST ESTIMATING PROCESS



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Guidelines established to assure compatibility between the individual facility cost estimates are:

(a) The cost of site acquisition is not included in the Phase III estimates.

(b) The only facility considered for integration into an existing facility is GD20 if it is located at AEDC. All other facilities are considered as being feasibly located on any appropriate site.

(c) Building envelopes have simple outlines established from equipment evaluation and plan drawings.

(d) Structures requiring a 70,000 lb/ft^2 (3.35×10^6 N/m^2) load bearing floor are priced to include piles driven 100 ft (30.5 m) to bed rock with a 10 ft (3.05 m) penetration.

(e) Services are defined as those utilities required to operate various facilities and test equipment. They include those provided by power, gas, and water companies; air; steam; and refrigeration. For Phase III, the services are provided separately to each facility with no provisions for consolidation, except for the case of GD20 if it is located at AEDC.

(f) All large electrical heaters are provided with individual gas turbine power generating plants to avoid load dumping and line problems in the event of a serious heater failure.

(g) Large electric motors are of the synchronous type and have small wound rotor motors as starters to bring them up to synchronous speed. All motors coupled to heavy mechanical loads are provided with controls and couplings to start them in the unloaded condition to ease the effects of high starting surge currents.

(h) Equipment definitions are directly associated with performance requirement to achieve a desired capability in a particular facility.

(i) Data acquisition equipment is defined as that equipment required to record, store, compute, and playback data collected during facility operation. For the flow facilities it is based on an estimate of required channels and costs extrapolated from existing facilities. For the non-flow facilities it is based on the number of control channels necessary and the number of environmental parameters being simulated, as determined from the facility component breakdowns.

(j) The instrumentation comprises thermocouples, strain gauges, pressure transducers, flow meters, accelerometers, microphones, and any other devices which are required to sense physical factors required for facility control and data.

(k) Low bay office areas are erected on a 6 in (15 cm) thick concrete slab using steel framed window wall construction and are estimated using Richardson's <u>Commercial - Industrial Estimating and Engineering Standards</u>. These areas have dropped ceilings, air conditioning, and 100 ft candle (1076 $lumen/m^2$) lighting. Space is provided on the basis of 85 ft^2 (7.9 m^2) per man and air conditioning is provided on the basis of one ton * per five hundred square feet (7.56 $watts/m^2$).

(l) Industrial structures covering test sections, test cells, model assembly areas, shops, and utility rooms are erected on a 6 in (15.2 cm) thick concrete slab using steel framing to support an insulated curtain wall and a built up roof. Commercial-Industrial Estimating and Engineering Standards is used to estimate the cost of these areas. Lighting is provided at 100 ft-candles (1076 lumen/m^2). There are no provisions for air conditioning.

(m) All estimates are in 1970 dollars. In instances where historical costs are used, Means Industrial Index (Figure 2-3) is employed to adjust these costs to a 1970 level.

Generally, the procedures, techniques, and base costs used are found in Commercial - Industrial Estimating and Engineering Standards published by Richardson Engineering Services, Inc. of Downey, California.

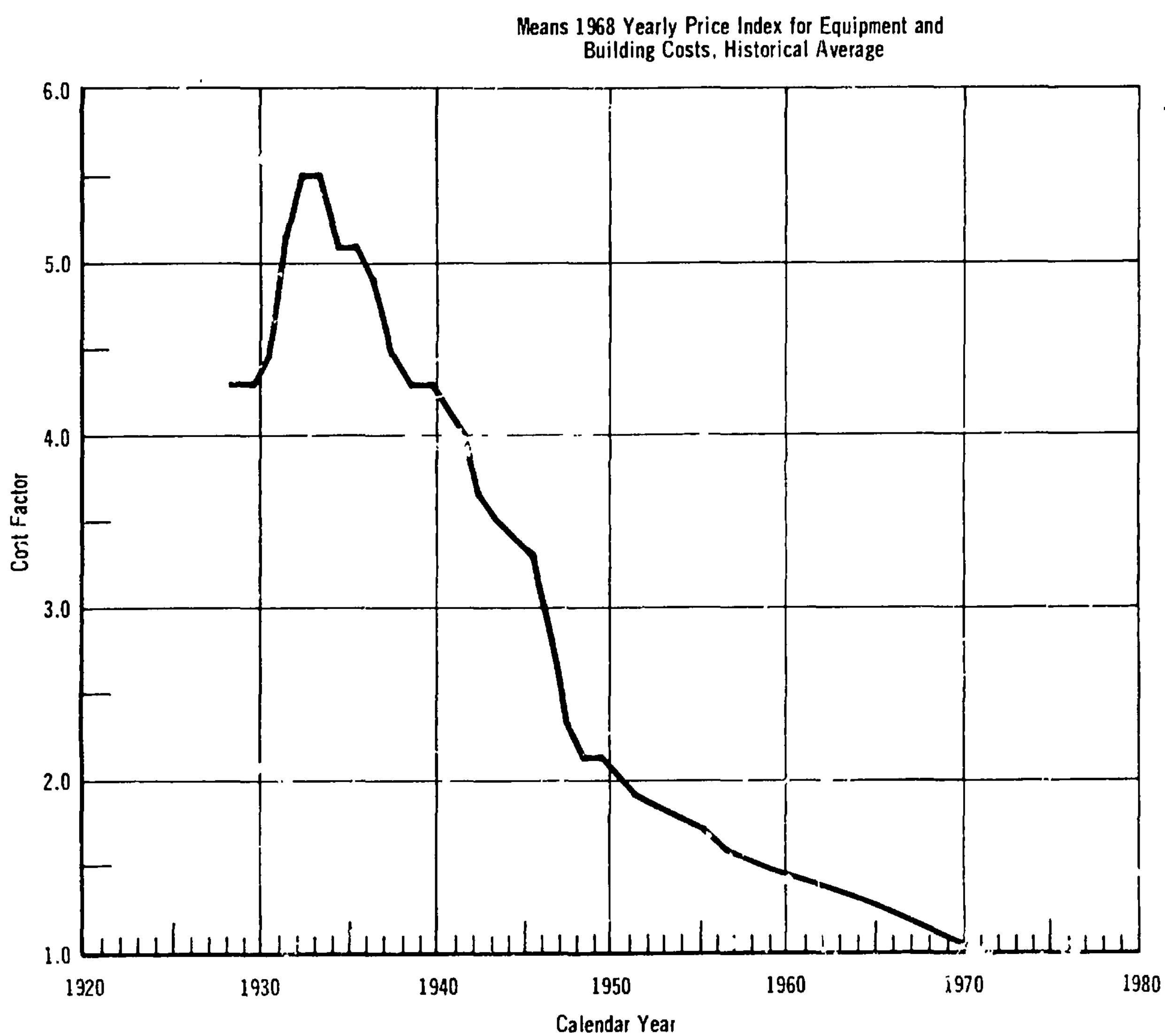
The following sections describe some of the general principles and quidelines used in estimating the costs of the various test facility components. Costs of providing power are discussed separately in Section 3.0.

2.3.1.1 CONCRETE - Using the above reference, concrete for footings and foundations was estimated on a cost per cubic yard in place basis and included concrete, form material, labor, overhead, and contractor profit. The cost per cubic yard is influenced largely by placement; i.e., the cost per cubic yard of footing or floor is considerably less than that for a foundation wall as considerably more forming material and labor is required to pour the latter. Reinforcing steel for concrete structures was priced on a per ton basis including material, labor, profit, and overhead. The actual cost used depended on the density and type of reinforcing steel required.

2.3.1.2 PRESSURE SHELLS - The test leg pressure shell structures were estimated by dividing them into structural elements and then describing these elements on a work sheet with respect to size, configuration, internal and external pressures, temperature, and corrosion effects. A simplified stress analysis of each element was also performed to determine the shell thickness and associated structural reinforcing requirements. From these factors, the appropriate structural materials were selected and their tonnages calculated. The complexity of fabrication was then considered and applied to the material type and tonnage requirements to determine the final cost per ton of each shell element. Pressure shell erection costs are dependent on the size and shape of each structural element and in the way the element is prefabricated for shipment to the site. Field welding constitutes a significant portion of these costs and a substantial effort was directed toward determining the types of welds and amount of welding required. For cases where field welding costs were not available in Commercial - Industrial Estimating and Engineering Standards, the Nooter Corporation provided data from which an estimate could be developed.

* One ton of air conditioning is defined as the thermal equivalent of one ton of melting ice in a 24 hour period and is defined as 12,000 Btu per hour (3.5 kW).

FIGURE 2–3
HISTORICAL COST FACTOR FOR EQUIPMENT AND BUILDING CONSTRUCTION ADJUSTED FOR A 1970 YEAR



$$\text{Cost Factor for 1970 Costs} = \frac{112}{\text{Price Index}}$$

Year	Index	Year	Index
1970	112	1940	27
1969	106	1939	26
1968	100	1938	26
1967	95	1937	25
1966	92	1936	23
1965	88	1935	22
1964	86	1934	22
1963	84	1933	20
1962	82	1932	20
1961	80	1931	22
1960	79	1930	25
1959	77	1929	26
1958	75	1928	26
1957	73		
1956	70		
1955	66		
1954	64		
1953	63		
1952	61		
1951	59		
1950	56		
1949	53		
1948	53		
1947	48		
1946	39		
1945	34		
1944	33		
1943	32		
1942	31		
1941	28		

Components such as nozzles, ejectors, and contoured shapes were similarly analyzed. Where machining was required, the estimate was prepared on the basis of using a tracer mill. Material selection for these components was dictated primarily by temperature extremes and corrosion effects. In cases where refractory metals had to be used, material costs were provided by Fansteel Corporation and coating and fabrication costs were supplied by MDAC.

2.3.1.3 INTAKE AND EXHAUST TOWERS - Intake and exhaust towers for the flow facilities were estimated using reinforced concrete construction. The recent acoustic treatment given to the exhaust towers of the MDAC Astrophysics Laboratory provided the basis of estimating the same for the flow facility exhaust towers. MDAC was required to comply with the very stringent noise abatement requirements of the City of El Segundo, California. Thus, the cost estimates for flow facility exhaust towers are biased towards the anticipated noise abatement requirements of a populated area.

2.3.1.4 INDUCTION HEATERS -Induction heater pressure shell structural material was selected after consideration of the maximum temperature to be attained and a simplified stress analysis to determine shell thickness and reinforcing requirements. A cost estimate was then developed as a function of material tonnage and fabrication requirements. The sheet copper shaded pole liner to shield the pressure shell from induced electric fields was estimated as a function of pressure shell interior surface area. Induction coil costs were obtained from Cleveland Coppersmith Company and Ajax Magnethermic Company. Stainless steel, TD nickel and refactory metal induction heater tube costs were provided by Fansteel Corporation and MDAC-ED. Costs for alumina and zirconia insulation bricks were obtained from Norton Company, and Fluidyne Engineering Corporation. Ajax Magnethermic also indicated that induction heaters of the type required for the flow facilities are feasible on the basis of their construction of a 250 megawatt unit for heating steel billets. However, they caution that the interactions of tube bundle design and fabrication, pole shading, induction coil placement and power supply voltage and frequency are very critical in developing an operable flow facility induction heater capability. Considering the effort required to achieve an operational capability for a much smaller induction heater at NASA-Lewis, a substantial prototype development effort should be considered before design and construction of a large unit is undertaken. For this reason, a development cost was included in the final cost estimate of each induction heater.

2.3.1.5 EXCAVATION AND EARTH MOVING- The structural test facility requires extensive earth moving and excavation for the reinforced concrete structural floor and hazardous test area. Costs for this operation were determined by developing a composite cost per cubic yard of meterial moved by including equipment rental, equipment operators, profit and overhead. These costs were estimated on a per cubic yard basis for a one way haul using Richardson's Commercial - Industrial Estimating and Engineering Standards.

2.3.1.6 MECHANICAL EQUIPMENT -Mechanical equipment cost estimates were obtained from direct written or verbal vendor quotes as indicated in Figure 2-1.

In several instances, special estimating techniques and procedures had to be developed from vendor or reference data to cover situations not in Richardson's Commercial - Industrial Estimating and Engineering Standards.

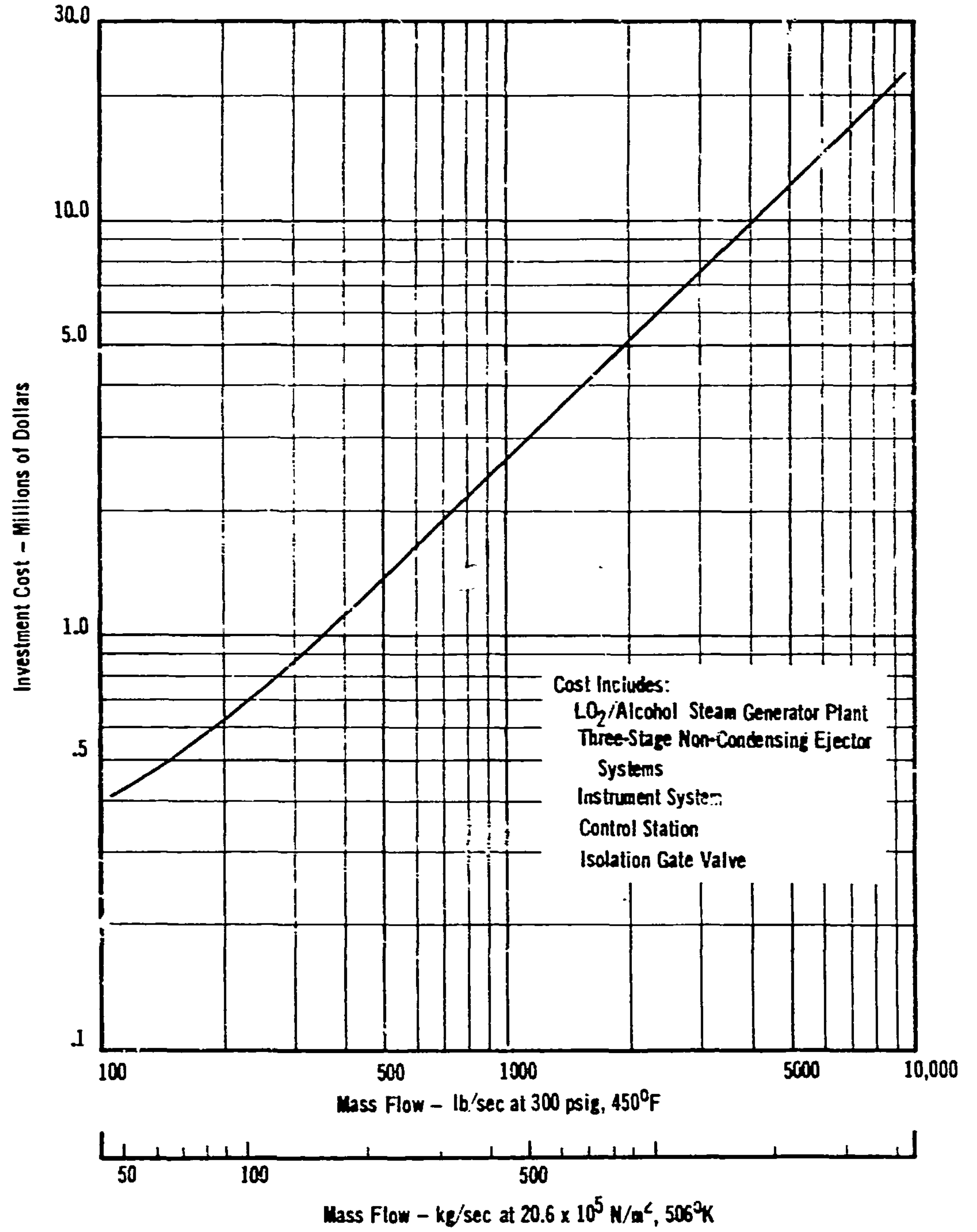
2.3.1.7 LO$_2$/ALCOHOL ALTITUDE SIMULATION SYSTEM -- Cost estimates for the S20 LO$_2$/Alcohol Altitude Simulation System were obtained from Figure 2-4. Data provided by Frank C. Brown & Company during the HYFAC study provided the data base for this figure. The cost curve includes LO$_2$/alcohol steam generators, three stage non-condensing ejector systems, instrumentation, controls, and the isolation gate valve. Brick and mortar supports for the steam generators, ejectors, diesel pumps, and related minor equipment are not included in these costs and may be determined from Richardson's Commercial - Industrial Estimating and Engineering Standards once the overall dimensions of the system have been determined. Electrical power requirements are a 100 amp, 28 volt DC supply and a 440 volt, three phase, 60 cycle supply. Costs for these services are also not included in Figure 2-4. These altitude simulation systems are best suited to operations where a very short evacuation to altitude time is necessary. A typical installation is shown in Figure 2-5.

2.3.1.8 CRYOGENIC SUPPLY- Cryogenic storage tank costs were obtained from Figure 2-6 and Figure 2-7. The cost curves were developed from data obtained from Linde Division, Union Carbide Corporation. To these costs were added the cost of transfer pumps and the cost of distribution lines.

2.3.1.9 VACUUM CHAMBERS - The vacuum requirements for S20 are provided by building a structure with sufficient framing to allow the attachment of a totally welded cold rolled, mild steel skin. Full opening, track mounted, electrically operated doors are provided at one end of the chamber. Those steel members providing contact between the doors and the chamber structure shall be milled to hold an inflatable seal and the doors shall be provided with a sufficient number of screw clamps to maintain the seal. Chamber evacuation to one Torr (133 N/m^2) in a very short time period is accomplished by use of steam ejectors operated in conjunction with a LO$_2$-alcohol steam generator. Steam boilers will maintain the vacuum after initial pump-down. The chamber was priced by determining the tonnage, fabrication, and erection costs of the steel. All other environmental chambers are priced using a curve (Figure 2-8) relating acquisition costs of environmental chambers to their diameter. The data used to develop these curves is tabulated in Figure 2-9. The spread of data in Figure 2-8 is accounted for by the wide range of test capabilities represented by these chambers and by their variations in shape, orientation, and amounts of cryogenic storage volume. The mean line indicated was used for cost estimation.

2.3.1.10 ACOUSTIC SHROUDS AND GENERATORS- Acoustic environments will be simulated by subjecting the test article to a high intensity sound field produced by electromechanical sound generators. The testing concept chosen was the plane-wave shroud method where the test article is surrounded by a shroud and acoustical generators create a high intensity sound field that impinges on the specimen surface. The cost of the acoustic generators was estimated by determining the cost of existing acoustic generation systems and extrapolating the cost for larger systems. In order to cost the acoustic shroud, the shroud was assumed to be made of structural steel. The proposed concepts for acoustical testing were patterned from present tests performed at MDC and at NASA-MSC, Houston. The costs developed for the acoustic system include the compressed air required to power the acoustic generators.

FIGURE 2-4
LO_2/ALCOHOL ALTITUDE SIMULATION SYSTEM
INVESTMENT COST



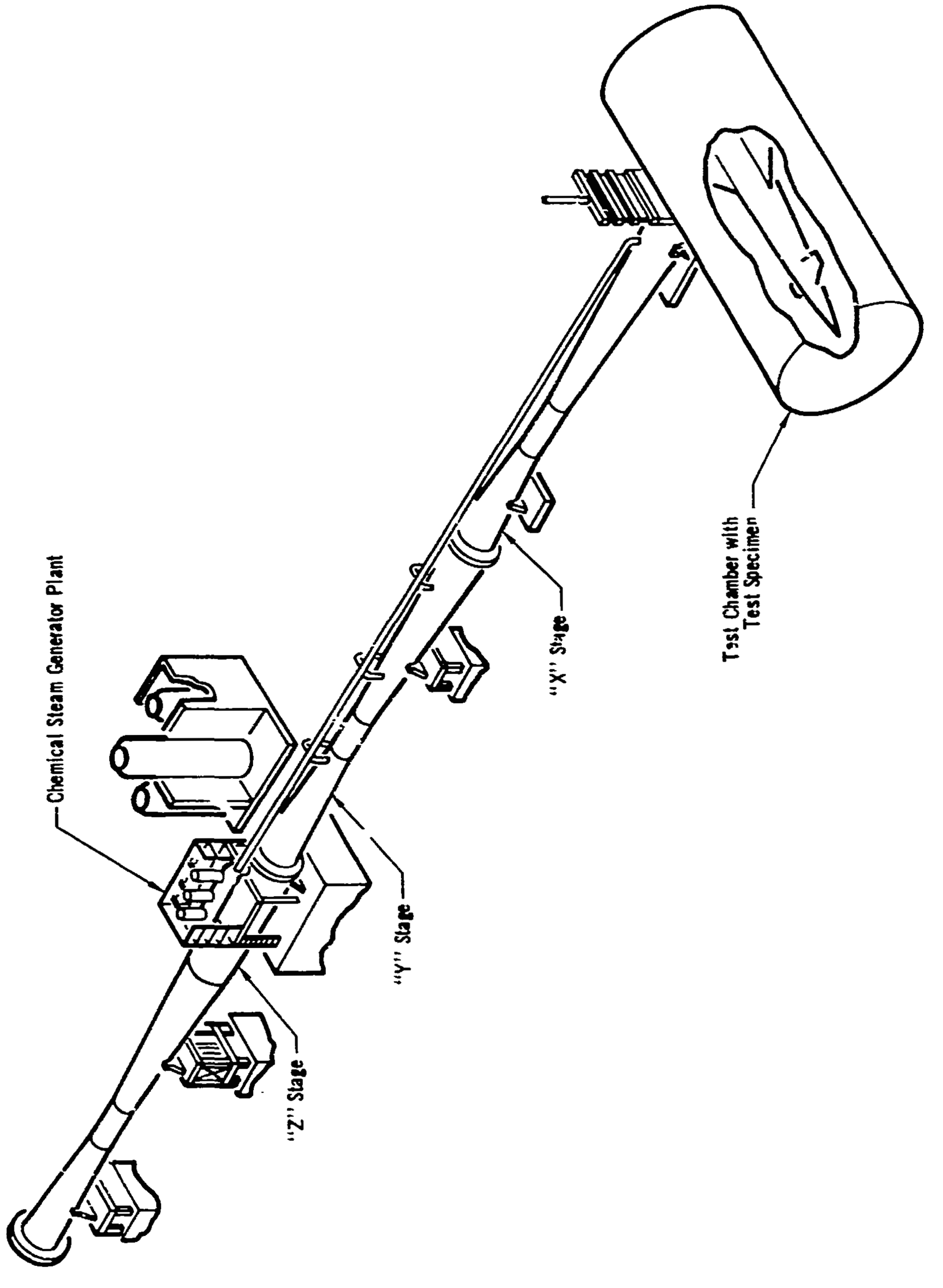


FIGURE 2–5
TYPICAL LO_2/ALCOHOL ALTITUDE SIMULATION SYSTEM INSTALLATION

FIGURE 2–6
LIQUID HYDROGEN STORAGE TANK COSTS

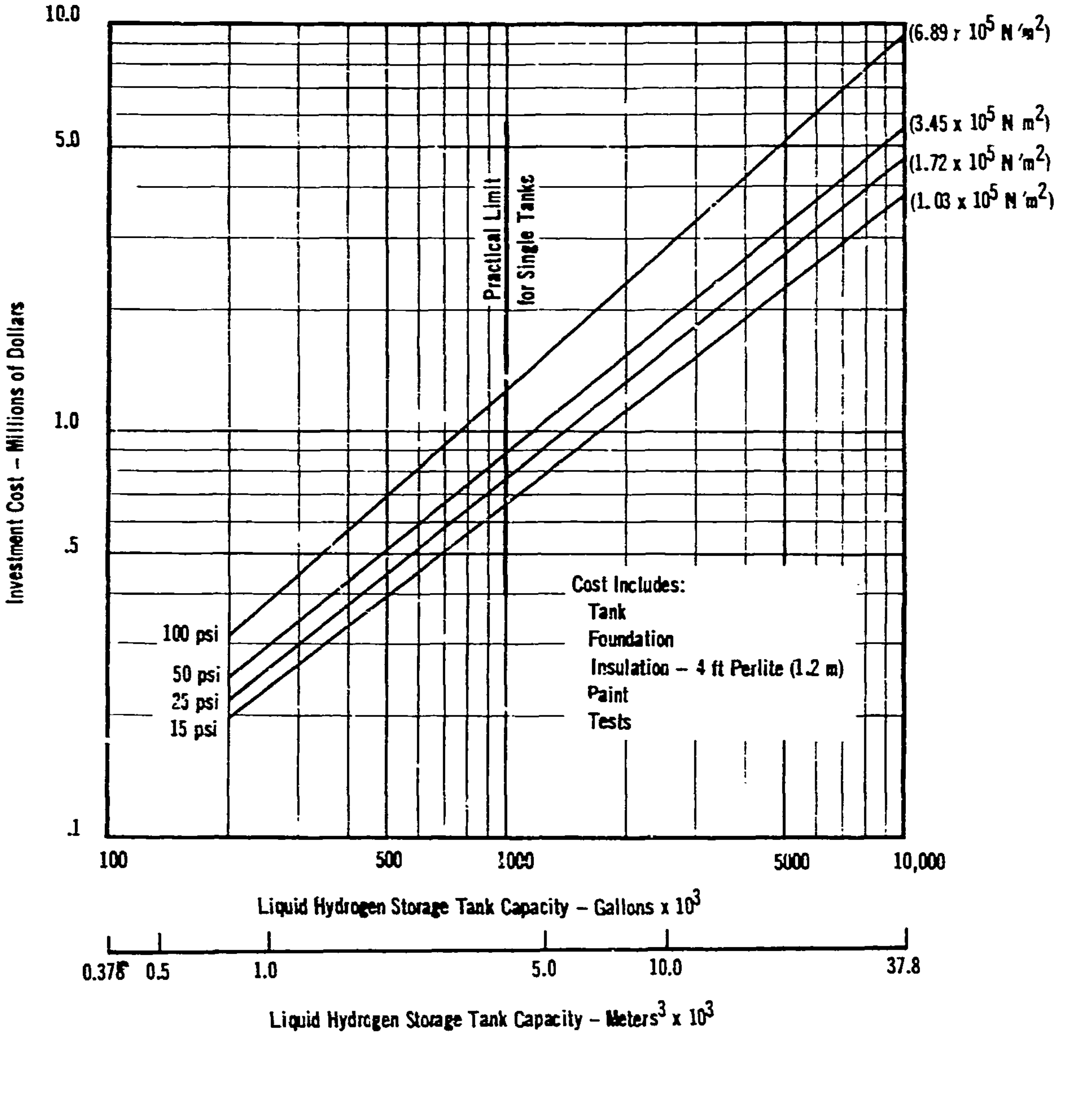


FIGURE 2–7
LIQUID OXYGEN STORAGE TANK COSTS

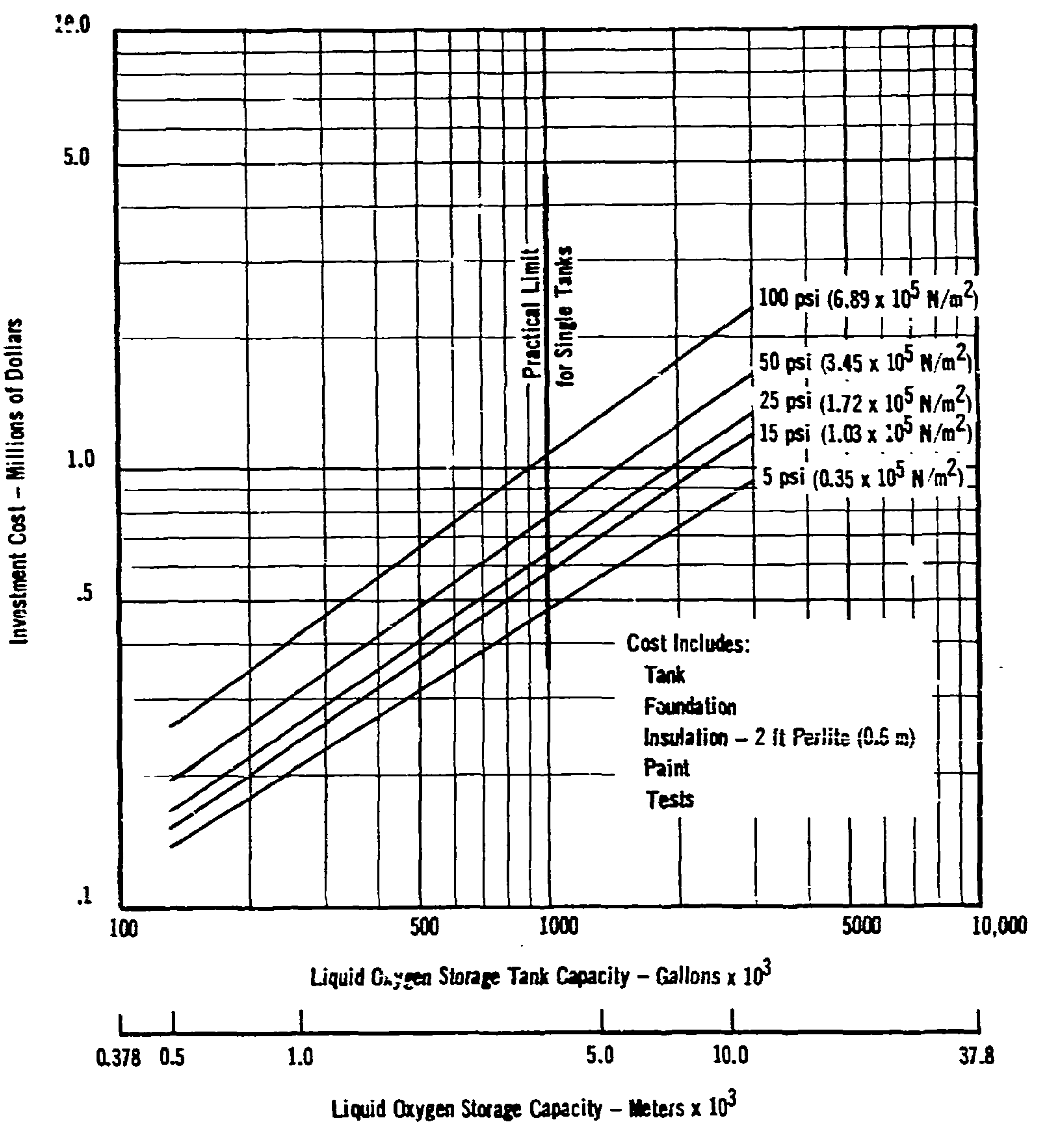


FIGURE 2-8
SPACE CHAMBER ACQUISITION COST AS RELATED TO SPACE CHAMBER DIAMETER

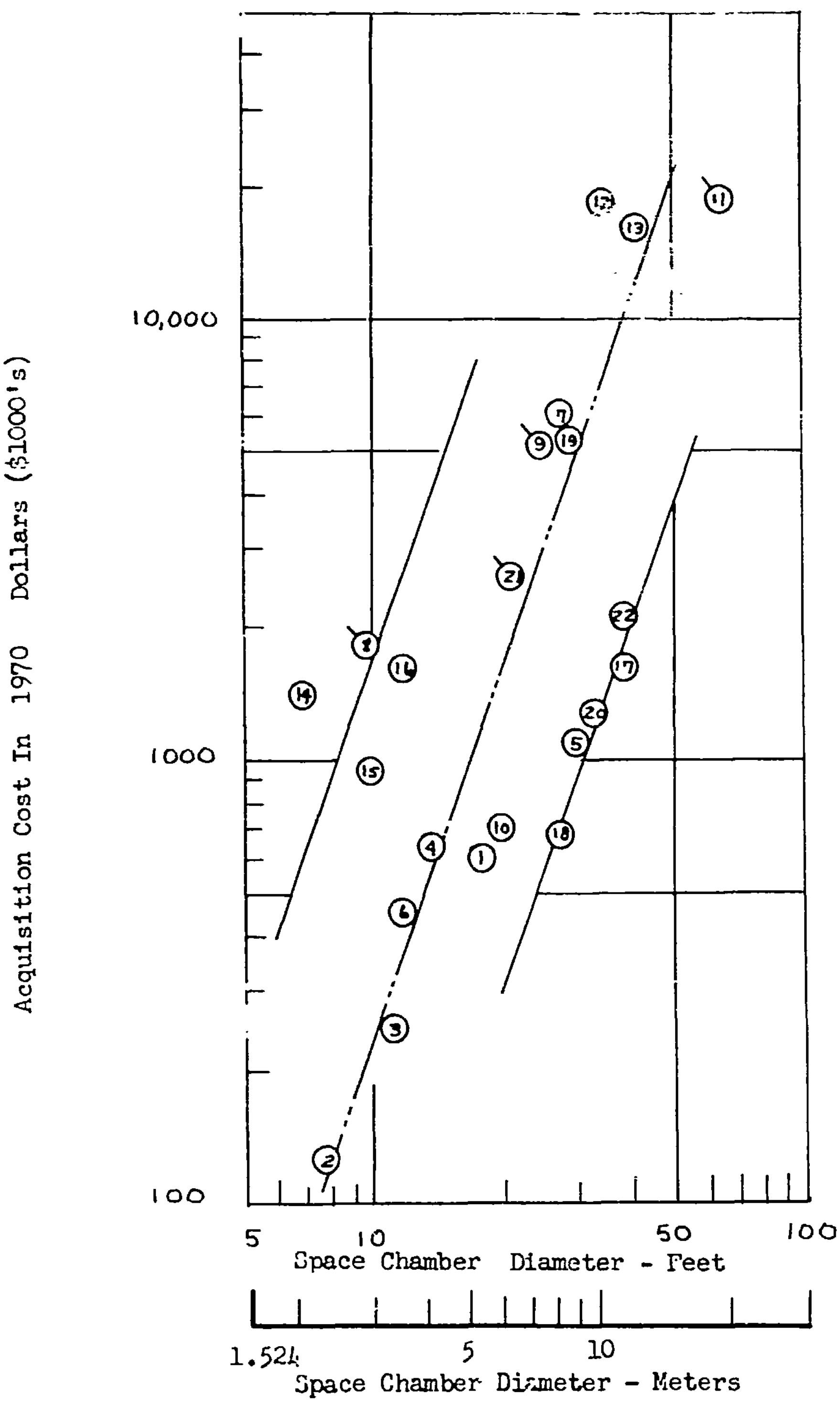


FIGURE 2-9
SPACE CHAMBER FACILITY DATA SHEETS

Facility	Year Built	Initial Cost x 10^3	Initial Cost in 1970 $ x 10^3	Dimensions ft (m)
McDonnell-St. Louis				
1. 18 ft Chamber	1963	497	628	18 dia x 30 (5.5 x 9.1)
2. 8 ft Chamber	1963	105	132	8 dia x 13 (2.4 x 4)
3. 11 ft Chamber	1953	155	260	11 x 9 x 25 (3.3 x 2.7 x 7.7)
4. 14 ft Chamber	1959	490	670	14 x 14 x 35 (4.3 x 4.3 x 10.7)
5. 30 ft Chamber	1963	923	1,160	30 dia x 36 (9.1 x 11)
NASA-Goddard				
6. Thermal/Vacuum Chamber	1963	379	475	12 dia x 15 (3.7 x 4.6)
7. Space Environ. Sim.	1964	5,015	6,000	28 dia x 40 (8.5 x 12.2)
NASA-JPL				
8. 10 ft Space Sim.	1965	1,577	1,890	10 dia x 45 (3.0 x 13.7)
9. 25 ft Space Sim.	1962	4,266	5,500	25 dia x 90 (7.7 x 27.5)
NASA-MSC				
10. 20 ft Chamber	1964	600	740	20 dia x 22 (6.1 x 6.7)
11. SESC Chamber A	1966	17,123	19,650	65 dia x 120 (19.9 x 36.6)
12. SESC Chamber B	1965	16,123	19,300	35 dia x 43 (10.7 x 13.1)

FIGURE 2-9 (Continued)
SPACE CHAMBER FACILITY DATA SHEETS

Facility	Year Built	Initial Cost x 10^3	Initial Cost in 1970 $ x 10^3	Dimensions ft (m)
AEDC 13. Aerospace Environmental Chamber (Mark 1)	1966	14,656	16,700	42 dia x 82 (12.8 x 25)
14. Aerospace Research Chamber (7V)	1960	1,108	1,480	7 dia x 12 (2.1 x 3.6)
15. Aerospace Research Chamber (8V)	1960	745	990	10 dia x 20 (3.05 x 6.1)
16. Aerospace Research Chamber (12V)	1960	1,231	1,650	12 dia x 35 (3.7 x 10.7)
17. GE/Valley Forge	1962	1,330 one chamber	1,710	39 dia (11.9)
18. STL	1962	550	708	28 dia (8.5)
19. Martin/Denver	1967	5,000	5,560	29 dia x 45 (8.8 x 13.7)
20. Xerox/Electro-Optical Sys. Div.	1967	1,200	1,330	33 dia x 22 (10 x 6.7)
21. TRW	1966	2,400	2,760	22 dia x 44 (6.7 x 13.4)
22. Philco-Ford/WDL	1967	2,000	2,220	39 dia (11.9)
23. Douglas-Santa Monica	1963	1,507	1,695	39 dia (11.9)

2.3.1.11 HEATERS AND THERMAL CONTROL- Elevated temperature environment up to 3,000°F (1660°C) can most satisfactorily be simulated by quartz infrared heat lamps. For thermal environments in excess of 3,000°F (1660°C), graphite resistance heaters will be used. Ignitron power controllers will be used to regulate both the quartz lamps and graphite heater curves.

A cost curve (Figure 2-10) was developed from an analysis of heaters required to produce a given heat flux per square foot of area and was used to establish quartz heater cost. Graphite heaters were specified when heat flux requirements exceeded 110 Btu/ft^2 (1.24 x 10^6 W/m^2) and were priced at $12,000 per square foot ($130,000/m^2) of test article area. Thermal control consists of a programming capability and a temperature recording/controlling capability using 250 kW ignitron units. Costs are five thousand dollars per channel of thermal control taken from recent MDC purchases plus heaters priced as previously discussed.

2.3.2 OPERATING COSTS - Operating costs are estimated by determining the quantities and costs of staffing, energy, consumables, and maintenance required to operate a particular facility as a function of test time, occupancy hour, or per year. The guidelines established to assure compatibility between the individual facility operating cost estimates are:

(a) The average energy rate for facilities to be located at AEDC is 6.15 mills per kilowatt-hour. This rate is based on an analysis of TVA billing to AEDC and includes usage, demand, and transmission charges.

(b) The average energy rate for facilities not located at AEDC or inside the TVA power network is 8 mills per kilowatt-hour, based on MDC billings.

(c) Those facilities requiring an independent energy source for a particular piece of heavy equipment or test apparatus are provided with hybrid power plants combining GE 7000 gas turbine generator sets and an exhaust temperature heated steam turbine generator at a cost of 7 mills per kilowatt-hour including maintenance and fuel. (Acquisition costs for such power units are included in the facility acquisition costs.)

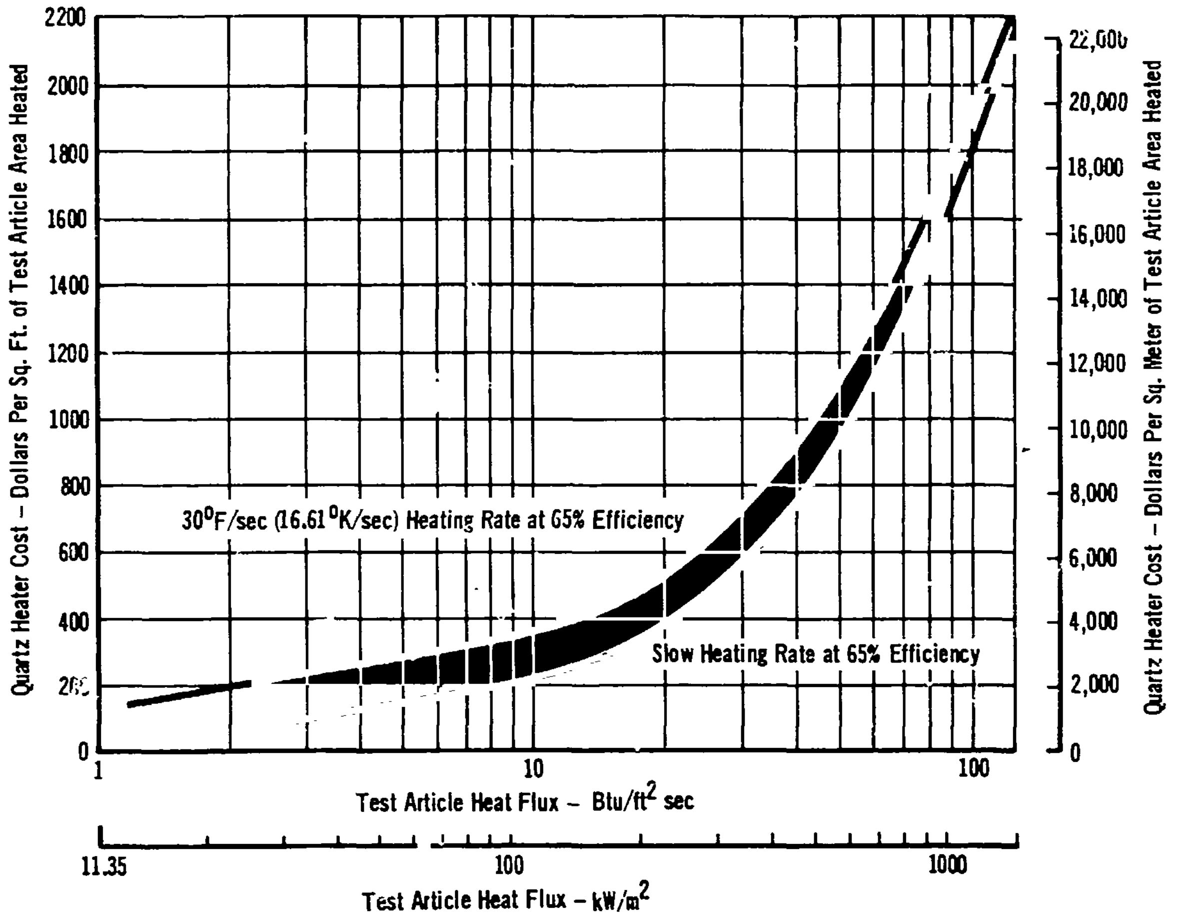
(d) Mechanical equipment and rotating machinery maintenance costs are $1.12 per horsepower per year ($1.50 per kW-year). Maintenance costs for electrical rotating equipment are estimated as one percent of the first cost per year. These costs include operating lubricants, miscellaneous operating supplies, and repair material. Maintenance labor is provided for under (f).

(e) Each facility is available for one 8 hour shift per day or for 2000 hours per year.

(f) Staffing is estimated at $20.00 per manhour for all grades of labor and includes direct and indirect costs.

(g) Consumables (cryogenics, carbon, jet engine fuel, etc.) for each facility are provided at current market prices and in quantities dictated by test operations.

FIGURE 2-10
QUARTZ HEATER COST AS RELATED TO TEST ARTICLE HEAT FLUX REQUIREMENTS



Application of these guidelines to the facilities results in: The following relationships which were used to calculate operating costs:

1. Energy Costs

$$\frac{\text{Energy Cost}}{\text{Occ-Hour}} = (P_{maximum})\ (U_R)\ (U_P)\ (R_P) \qquad (2\text{-}1)$$

Where:

$P_{maximum}$ is the maximum power (kilowatts) required for facility operation

U_R is the test utilization factor = t_{run}/t_{occ}

U_P is the power utilization factor = $P_{avg}/P_{available}$

R_P is the cost of energy in dollars per kilowatt-hour

For impulse facility operation, such as GD-7, it is easier to calculate energy costs on a per run basis as different systems (resistance heaters, booster pumps, compressors) are operated individually and concurrently for varying time spans to prepare for each run. Equation (2-1) then becomes:

$$\frac{\text{Energy Cost}}{\text{Run}} = \sum_{i=1}^{n} t_i\ P_{i_{max}}\ U_{Pi}\ R_{Pi} \qquad (2\text{-}2)$$

Where:

i Refers to the particular system

n Is the number of systems used

t_i = time that system i operates for one run

Energy cost per occupancy hour for impulse facilities is calculated by multiplying the cost per run by the average runs per occupancy hour.

$$\frac{\text{Consumable Cost}}{\text{Occ-hour}} = (W_{max})\ (CUF)\ (U_r)\ (U_c)\ (R_c) \qquad (2\text{-}3)$$

Where:

W_{max} is the maximum consumable flow rate

CUF is the consumable utilization factor = $\frac{\text{Amount Req'd}}{\text{Amount Used}}$ (for cryogenic fluids)

U_r is the test utilization factor = t_{run}/t_{occ}

U_c is the average consumable flow rate/maximum flow rate.

R_c is the unit cost of the consumable

2. Maintenance Costs

$$\frac{\text{Maintenance Cost}}{\text{Occ Hour}} = \frac{\text{Maintenance Parts Cost/Year}}{2000\ U_F} \qquad (2\text{-}4)$$

Where:

U_F is the facility Utilization Factor = $\frac{\text{Total Facility Occupancy}}{\text{Total Available Time}}$

3. Staffing Costs

$$\frac{\text{Staffing Cost}}{\text{Occ-Hour}} = 20\ (N_s)\ \left(\frac{1}{U_F}\right) \qquad (2\text{-}5)$$

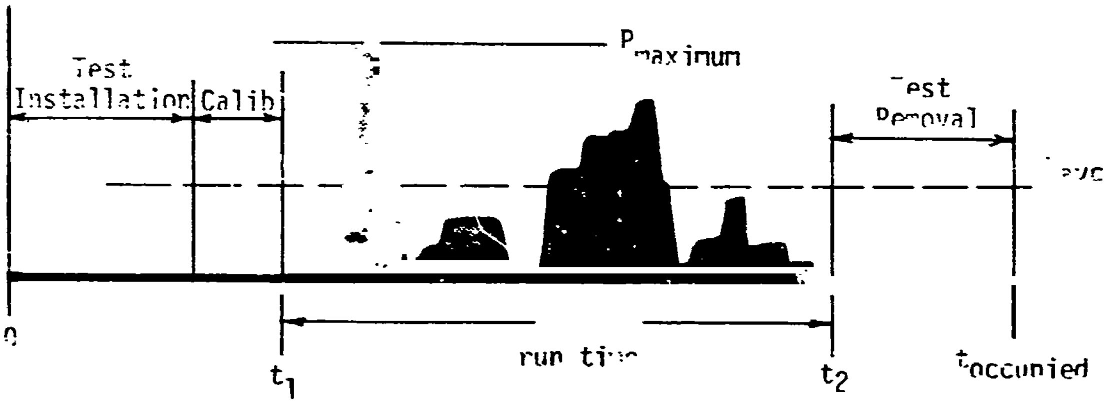
Where:

N_s is the number of direct staff and 20 is the \$/man hour cost of labor including direct and indirect costs.

The utilization factors and parameters associated with each of the equations must be determined as a function of the test schedule and test operations planned for each facility. HYFAC ground facility operating costs were calculated using Equations (2-1) through (2-5) and assumed utilization factors and parameters based on historical test activities.

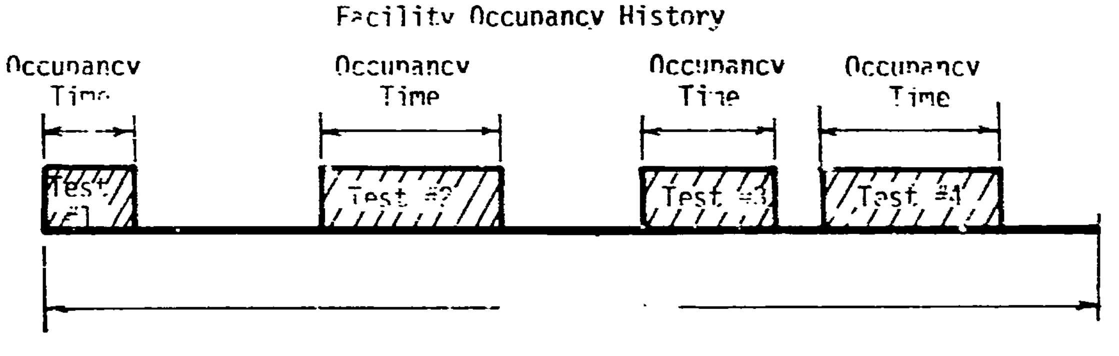
The power utilization factor and test utilization factors are functions of the distribution of the power required during a test program and the effectiveness of utilizing the available occupancy. These parameters can have wide variations in magnitude and seldom approach unity in value. Most of the historical data used as a basis to estimate these factors was obtained from the Arnold Engineering Development Center (A.E.D.C.) operating contractor (ARO Inc.) Plans Office. The following sketch is a representation of typical power requirements during a test program.

Power Use History



Likewise no facility is used 100 percent of the time for actual testing. Time must be allocated for test installation, removal, calibration, repair and maintenance; as well as the occupance of unscheduled time. A representative spectrum of facility utilization factor is indicated by the following:

Facility Occupancy History



2.4 DEVELOPMENT ASSESSMENT GROUND RULES

Each ground test facility is evaluated with respect to the degree of technical risk present. This evaluation is done in terms of confidence level, as was done in Phase II. Whereas, in Phase II. a confidence level was assigned to the entire facility, a more sophisticated analysis was done in Phase III. Confidence levels for each major facility component or system were assigned, and the composite facility confidence level was calculated by the weighted average of the individual system or component confidence levels. The weighting factor is proportional to the cost contribution of the individual element to the complete facility cost.

CL_F = Facility composite confidence level

CL_i = Confidence level of element i

K_i = Weighing factor element i = [illegible] of element i/total facility cost

n = Number of facility elements

$$\text{so: } CL_F = \sum_{i=1}^{n} K_i \, CL_i \qquad \left(\sum_{i=1}^{n} K_i = 1.00 \right)$$

The chosen weighting method assures that the individual confidence level contribution of each element is scaled proportionally to its cost contribution and, presumably, importance. It should be noted that the confidence level of estimated costs are proportional to the technical confidence level since, as the element or facility confidence level decreases, more and more experimental or developmental prototype work is required, and the likelihood of unplanned extra costs or delays, or possible re-design or selection of substitute techniques increases. No concrete relationship between confidence level and cost uncertainty can be developed, but an appreciation of relative cost certainties between the various estimated facilities can be gained by comparison of their facility confidence levels. Confidence level definitions are listed below. They include the premise upon which the ratings are based, as well as an appraisal of the types of problems encountered, development required, and quality of cost estimates at each level.

o <u>Level 5</u>. This level assumes all of the hardware necessary for the facility test leg, system, or component is available in industrial usage in the size and performance levels necessary to satisfy the facility requirements. In assembling any ground research facility of the complexity of those in this study, even though all of the individual components operate to specification, the system interactions will produce functional problems which must be solved before complete facility operation is achieved. These problems are not necessarily minor in nature and can require a significant time period, and/or replacement of equipment to remedy the situation. For this case, the confidence that the operational goals will be met and the facility will function as specified are excellent. The de-bugging of the problems that occur during facility shakedown will occur regardless of the technical risk associated with realization of the specified performance. This level represents high confidence and low technical risk with the problems arising from normal construction/fabrication sources rather than non-realization of equipment design goals.

o Level 4. This level assumes that all of the necessary hardware is developed and in industrial usage, but not quite at the size and/or performance levels required, necessitating a reasonable extrapolation of existing experience. In addition to the expected integration problems associated with Level 5, there is an additional risk that some of the equipment may not initially attain their performance goals, requiring additional development time. The confidence associated with achieving the desired goals at this confidence level is still high, although the potential to encounter additional development problems is greater. Attention to small details and prototype qualification can reduce these risks if the acquisition schedule permits.

o Level 3. This level assumes that the principles of operation of the facility or system have been verified in smaller scale existing facilities and industrial equipment, so that there is no technical reason which would prevent attainment of desired goals in all equipment functions as desired. The hardware is of such a size and performance however, that new designs and/or concepts are necessary to supply the needed conditions. For this level of confidence, without an equipment development program, the confidence in initially achieving the specified performance goals is greatly reduced from Level 4. Some problem areas may require only minimum development programs, but those associated with large, high performance hardware could require a substantial development program.

A development program of this scope may increase the hardware costs between 1.5 to 2 times the initial estimated acquisition costs. The confidence level is high that the specified performance of the over all facility or system will be attained, but its attainment is dependent on an adequate development program. Again as in Level 5, the ever present integration problem must be considered.

o Level 2. This level represents a situation analogous to Level 5, in that most of the support equipment exists in the size and performance necessary to achieve the over all performance. However, the technical principles associated with the facility concept and/or design represent new approaches and techniques not previously applied in the proposed manner. For this level a development program is necessary to acquire the nessary details to correctly specify the support equipment as well as demonstrate the operational suitability of the concept. Providing the supporting equipment specifications do not materially change, then the primary additional costs will be in developing the new designs. This could increase the cost of the individual components by as much as a factor of 5, but the total impact on the overall costs would be substantially less, perhaps similar to Level 3. Since the basic principles underlying the facility concept need verification, the level of risk is higher than that associated with Level 3. Failure to verify the design concepts would require reassessment of the facility feasibility or necessitate development of satisfactory alternate design concepts.

o Level 1. This level assumes that the facility concept proposed is based on theoretical analyses and has not been demonstrated in actual hardware at the performance levels and size proposed. This represents the minimum confidence level and greatest technical risk, requiring development of a prototype system to verify the concept as well as development of the necessary support equipment for the full scale facility resulting from the prototype tests. Even with a prototype program, integration of hardware into a complex facility array while developing the basic facility concept itself could result in very costly additional development programs and delays. For this level the final cost of the facility which achieves the specified design goals could approach 5 to 10 times the initial estimated cost if significant development problems are encountered. This level represents a high risk, with a high probability that serious problems could be encountered.

It is of interest to identify the facility components which contribute the majority of the technical risk inherent in each facility concept. This can be done quantitatively by noting that the confidence level is inversely proportional to the level of technical risk. The technical risk factors are related to the confidence levels as follows:

CL	TR
5	1
4	2
3	3
2	4
1	5

A composite technical risk evaluation can be made for the entire facility by the same procedure used for the composite confidence level, that is, weighting the individual values by the cost fraction of the individual facility element and summing. These values are tabulated in terms of the percent risk contribution to the total facility technical risk.

2.5 GROUND RULES FOR THE ASSESSMENT OF SAFETY ASPECTS AND CONTROL SYSTEMS

The facilities considered in this study utilize high pressure-high temperature air at extremely large flow rates which means that careful attention and consideration must be given to the protection of personnel and equipment. The design of any of these facilities must recognize and provide for off-design conditions which may be encountered in the various components during test run preparation, actual test running, and run abortion or emergency shut-down.

To systematically prepare facilities of this nature to a run condition involves the establishment of detailed operating procedures and interlock circuits, not only for the test legs, but for the entire system, including observation and data elements. Each component of a given facility must include elements which sense conditions indicating that the component is not ready for a test run. During design, it is then essential to establish the off-design conditions and compatible sensors or monitors which can be combined into an integrated system whose output can be used to prevent or shut down a run. Generally, the gas dynamic facilities, being less complex than the engine facilities, will require operating procedures and permissive circuits smaller in scope and complexity but complete in terms of safety.

The difference between an off-design loading and a safety hazard load is a matter of degree. Safety hazards can simply be conditions which, if left uncorrected, will lead to excessive loads. The primary safety requirement is therefore to sense an impending off-design load and prevent it from becoming excessive. In some cases, this is not possible, due to time or other factors relating to the specific component, and the only recourse is to relieve the excess load before it becomes large enough to cause damage. It is therefore necessary that each component be studied from the off-design standpoint as well as from the stated design criteria standpoint to assure that a safe design results. Defining or describing what constitutes safe design is not possible except with respect to the design details of a given component. The purpose of the following paragraphs will be to review some of the general factors which must be considered in arriving at a safe design for a tunnel circuit as a whole and for individual components.

Personnel safety problems should be at a minimum for these facilities during the actual test cycle since the test areas will be evacuated. The primary safety task for actual facility runs will be to make absolutely certain that personnel are not inadvertently left in the test area during a run. The test area should be equipped with a loud speaker system and warning horns to relay test area evacuation commands. In addition, the facility condition should be presented by a series of colored lights mounted throughout the facility.

Access to remote areas of the facility such as fuel storage areas and the interior of exhauster ducting, mufflers and large diffuser sections must be controlled. This can be accomplished by including the keys to these areas in a plant interlock system which would prevent initiation of tunnel operation until all keys were returned to their interlock panel.

A system of personnel safety switches should be installed throughout the hazardous areas of the facility. In the event that an individual was inadvertently left in a hazardous area after the test area evacuation command, these switches could be used to prevent further tunnel operation.

Serious safety hazards may arise due to the noise generated by exhausting the tunnel flow to atmosphere. Personnel should be prohibited from the areas of most intense noise generation. The control building and rooms should be designed to minimize outside noise interference.

The potentially very large energy levels of sound generation will also present serious [illegible] to the tunnel equipment. The sound and vibration may be transmitted through [illegible] by the ducting and support structure. Tunnel equipment should [illegible] mounted such as to reduce the effects of the high sound lev[illegible].

[illegible] safety hazards will undoubtedly occur during normal model [illegible] preparation and maintenance. These facilities do not create [illegible] particularly unique in this regard. Standard industrial safety practices should be adequate for personnel and equipment protection when an actual test is not in progress.

It would be exceedingly difficult and impractical to instrument these facilities to monitor all possible trouble spots. General areas of all facilities should therefore be provided with television coverage during a run. The television cameras should be remotely controlled and should be able to provide a picture of a general facility area or obtain a closeup of any desired tunnel component. Television coverage of the test article will naturally be necessary, but additional cameras should also be considered for observation of the heaters, nozzles, diffusers and specific spray cooled items. Television coverage of these facilities, especially the engine facilities, will probably be more extensive than current similar operations simply due to the relative size and the requirement that personnel evacuate the test area.

For facilities of this nature, it is necessary to establish a process control system which is normally limited to those controls necessary to establish, maintain, regulate and stop the flow. The process control does not include model controls, data acquisition or control of the auxiliary support system such as water treatment, air storage systems and exhauster systems.

At the high flow rates which are anticipated for these facilities, it will be necessary to minimize the time required to establish test conditions once the cycle has been initiated. An automatic control system which performs the start sequence in a preprogrammed order will keep the required start time to a minimum. To assure that the critical tasks associated with starting and stopping are accomplished in the proper sequence will require a system of interlocks. These interlocks must be operative in any mode of control, automatic or manual.

The interlocks incorporated into the process control system are intended to prevent the initiation of a facility start before all systems are in proper configuration and before all necessary supporting operations have been carried out. The information regarding which steps have been carried out in a prerun process should be quickly available to the tunnel chief operator. One method of presentation would be a lighted annunciator panel which contains each of the necessary prerun interlocks on a small lighted segment.

The interlocks would be both manual and automatic. The manual interlocks would consist of a switch which would be placed in the run position only after its associated task had been completed. The manual interlocks would be used primarily for tasks involved in selecting the desired run configuration. Manual interlocks would be simply an electrically operated check list, but they would have the merit of being in the critical path of the tunnel operational sequence. The tunnel could not be operated until the interlocked tasks had been accomplished and the proper switch thrown. Manual interlocks have the serious fault that the switch might be inadvertently placed in the run position before the associated taks had been accomplished. This possibility must be avoided by careful attention to the verification of all control operations by the chief operator.

Automatic interlocks are those which are governed by external sensors or transducers. The automatic interlock would be controlled by the signal supplied from the external source. This type of interlock should also be incorporated into the sequencing system to initiate an automatic shutdown procedure if one of the sensors indicate an unsafe condition.

Interlocks can be divided into four general classifications: configuration, auxiliary system, operating and performance monitor. The following is a general description of each classification.

Configuration Interlocks

Configuration interlocks are those relating to the selection and verification of the proper operating conditions of such items as air supply, exhauster plant, cooling water, heater and fuel system. Most configuration interlocks are manual.

Auxiliary System Interlocks

Auxiliary system interlocks are those which verify the status of the support subsystems relating to facility operation such as stored cooling water level, barometric well level, demineralized water supply hydraulic supply pressure and data acquisition system. Most of these interlocks are automatic.

Operational Interlocks

Operational interlocks are those which relate to the process and operations necessary to get the facility started. This group of interlocks is normally the largest in number and are automatic. Typical operational interlocks are: safety areas secured and locked, combustible vapors not present, test cabin closed and locked, diffuser cooling water flowing, nozzle cooling water pressure set, heater stack valve closed, electrical heater cooling water set, and refractory heater reheat system secured.

Performance Monitor Interlocks

The performance monitor section of an interlock panel is intended to show any unsafe condition which may develop after the start and run sequence has been initiated. All interlocks in this group would be governed by external sensors and transducers. When an unsafe condition develops, an interlock is actuated and a control sequencer is automatically switched to an emergency stop mode. Typical performance monitor interlocks are: nozzle throat temperatures, mixer pressures and temperatures, ΔP across a refractory heater bed, diffuser temperature, heater pressure and model or model support temperatures.

The method of operation envisioned for an interlock annunciator panel is for the tunnel chief operator to first clear all configuration interlocks. The manual interlocks are cleared by verifying or setting up a certain condition and then throwing the associated interlock switch. The automatic interlocks will clear themselves as their associated system is put in run condition.

The auxiliary system interlocks are cleared after the configuration interlocks. All auxiliary system interlocks are automatic with the exception of Data Acquisition Systems which could be manually cleared by the lead instrumentation engineer.

The chief operator next checks and clears the prerun operating interlocks. Personnel may be in the test area until a Test Building interlock is cleared. The facility may be held for extended periods after the prerun interlocks are cleared if it is necessary to wait for power, water or plant exhauster support. Long "hold" periods may, however, reduce the outlet temperature of facilities which contain storage heaters in the system.

2.6 CONSTRUCTION TECHNIQUES

The development of techniques in the areas of field fabrication and assembly may well be prime considerations in the determination of facility schedule and cost.

A large portion of the fabrication will necessarily be accomplished on-site and consideration must be given to the determination of weld integrity and the final proof testing of pressure vessels utilizing hydrostatic or penumatic pressure testing techniques. If hydrostatic test procedures are to be employed, the above considerations should be injected into the design early, such that provisions are made for additional bulkheads and support structures to carry the water loads.

The erection of any of these facilities will require use of crane and hoist equipment. Some of the facilities, such as the turbomachinery and scramjet facilities, which have large test articles and many large piping configurations will require permanent hoist equipment to allow timely configuration changes and maintenance to the facility. These requirements should be coordinated during the design phase and in evolving the construction plan.

2.7 GENERAL SITE CONSIDERATION GROUND RULES

There are two aspects to this section: first the assumptions made concerning the degree of site development existing at the time of facility fabrication, which influences the acquisition costs, and second, the factors which should be considered in the selection of the facility site and in the integration of the facility into its surroundings.

The first aspect of site consideration assumed that suitable locations could be found at existing government facility complexes and there was no requirement to develop a complex where one does not presently exist. Based on this assumption the following ground rules were applicable to the development of facility acquisition costs in terms of site preparation.

(a) The real property is owned and available from the government.

(b) Generally a large quantity of electrical power will be available. Additional power requirements will be provided by running in high voltage power lines transformed at a switch yard, located at the facility site, to 15 kV. The costs associated with this additional power can only be estimated after a particular site is selected. Payment to the utility company for the cost of running in the additional transmission lines will probably be in the form of an amortized monthly charge, so that the operating costs rather than the acquisition costs will be affected.

(c) The amount of earthmoving and excavation assumed an unprepared site with some removal of foliage. The amount of excavation is a function of each facility concept requirement.

(d) A source of cooling water, and a location for proper disposal of the heated cooling water is in existence at the government facility complex.

(e) No provisions are made for access roads, fencing, and utility supply except adjacent to the particular facility site.

The second aspect of site consideration concerned the ground rules associated with selection of a site suitable to accomodate the specific facility. The factors which were considered important in determining a suitable site were:

(a) Availability of needed electric power - Because of the magnitude of the power required for most of the candidate ground research facilities (exceeding 1,000,000 kW), this could have a major impact on the acquisition costs if the local utility network could not supply the required power. In this case, on-site, facility owned generating equipment, in excess of that already contained in the individual facility cost estimate, would be necessary.

(b) Cost of electric power - As discussed in Section 3., even if the power were available, the electric power costs can vary by over a factor of three just due to geographic considerations, not including variations in demand charges with locale.

(c) Availability of needed cooling water - The large amount of cooling water required, particularly by the engine research facilities,means that an independent water supply, specifically provided for that purpose, not dependent on local rivers or lakes be provided. This is especially true when considering the thermal contamination possible by the used cooling water. Sites having such an arrangement would be a primary consideration for the engine research facilities. The cost of providing such a system would have to be added to the facility acquisition costs if not available at the selected site. For the other ground research facilities the cooling water requirements probably represent no greater a requirement than currently exists at present research facility complexes.

(d) Land availability - Here the context is land availability within existing government facility complexes.

(e) Access by road, rail, and water transportation - The shipment of outsized cargos during facility fabrication makes this an important consideration. Cost estimates were based on the assumption that sufficient transportation existed.

(f) Soil characteristics and bedrock depth - All of the candidate ground research facilities, and especially the structures facility, will require favorable soil bearing strength, and reasonably close bedrock formation. Alluvial soils and marshlands could very possibly not be suitable for facilities of this type and careful consideration should be given to increased costs which may result from unfavorable soil conditions.

(g) Availability of technically qualified labor

(h) Availability of normal support services, such as plant maintenance, model making facilities, machine shops, general purpose computer capability, instrumentation and calibration groups.

(i) Availability of major services or equipment, that is, the proximity of other research facilities with compressors, exhausters, water, and electrical power available so that a long term breakdown of facility hardware might be shunted around using another facility's services to maintain limited operational capability.

(j) Need for remote site locations - The possibility of high noise levels and safety hazards may preclude the erection of these facilities near populated, incorporated areas (see appendix A). Considerable additional cost could be encountered by incorporating these facilities in a heavily populated area.

(k) Effect of facility on local ecological balance - The candidate ground research facilities refined in Phase III of this study are generally of a magnitude seldom attempted for research facilities. However, the analysis of the Research Objectives points up the fact that large facilities will be required if the sizable aircraft systems postulated in the nine potential operational hypersonic aircraft are to be an eventual reality. Serious degradation of the local ecology and the physical environment of its human inhabitants could occur because of the large power requirements, mass flows, and cooling requirements of these facilities if special consideration is not given to the facility sites and the impact of the facilities on their surroundings. Therefore, general site considerations should consider the entire facility complex as the effect of the influx and outflow of materials and power on the surrounding area. There appears to be sufficient technical expertise available that any of these major experimental research facilities could be integrated into their respective sites without damaging the surrounding environment or imposing unacceptable conditions on the adjacent inhabitants; providing the total system is considered.

2.8 GENERAL FACILITY ACQUISITION SCHEDULE CONSIDERATIONS

There are many factors which influence the schedule on which major facilities can be acquired. These factors can be usefully separated into two basic categories: (1) those related to policy and fiscal planning, and (2) those related to the design of the facilities. Only the latter are considered here.

A primary objective in designing the HYFAC facilities was to stay within the state of the art which could reasonably be expected to exist in the mid-seventies. As a result no technological breakthroughs appear required; however, new applications of existing know-how are anticipated. Examples of the latter are (1) the use of combustor technology, which exists in industry, in the different environment of an aeronautical test facility (as in E9) represents a new application, and (2) the field fabrication of extremely large pressure vessels represents a growth application of an existing technology. There is no real question of feasibility in either case, the necessary equipment and techniques having been demonstrated by previous actual application.

This transfer and growth of technology represents the major development activity required for these facilities. In some areas, involving a transfer of technology, the development activity should be concurrent with the evolution of the design of the facility. This is necessary in order that this process be completed at the time that contracts for the facility are let so that competitive pricing and reliable schedules can be obtained. The development of growth areas will, on the other hand, take place almost entirely during fabrication and construction. It will be the result of the need of the contractor and his associates to develop the capability to do a sought after job and to minimize their costs in doing it. One of the most difficult aspects in designing advances in the application of the state of the art is the assessment of what quantum step is practical and useful in any given case. The final decision involves close liaison with manufacturers, fabricators, and constructors in general. The problem is often complicated by the fact that the most advanced and rapidly advancing capabilities are proprietary in nature - this may well be the case in the specific areas of combustor technology and pressure vessel fabrication techniques. To achieve the best possible facility, arrangements for incorporating proprietary hardware and skills should be recognized and resolved early in the facility planning.

The basic elements of the acquisition process are essentially as follows:

1. Preliminary Studies
2. Definition of Specific Facility Performance and Construction Concepts
3. Development of Design Criteria and Cost Estimates
4. Preliminary Design and Cost Estimate
5. Final Design and Cost Estimate
6. Definition of Bid Packages and Construction Plan
7. Letting of Bids
8. Preliminary Site Work and Shop Fabrication
9. Field Fabrication, Installation, and Final Site Work

10. Demonstration Tests on Components
11. Demonstration Tests of Subsystems
12. Overall Facility Demonstration Tests
13. Operation of the Facility for Calibration and Shakedown.

These categories are essentially the same for all of the facilities studied. It, therefore, should be noted that, concurrent with the design, the development work related to the transfer of technology must be resolved; and concurrent with the design and construction of the operating methodology must be determined and the operating staff assembled.

The calendar schedule for the facilities studied is necessarily based on an extrapolation of past experience. Consideration was given to the available growth in technology which can be applied to their design and fabrication. The use of special skills which are of limited availability must be anticipated and be reflected in the acquisition schedules, i.e., the schedule cannot be substantially reduced by assembling a very large team - at least not without attributing something of the order of a national priority to the effort. A reasonable and typical schedule for each of the facilities refined in Phase III is shown in the appropriate sections of this volume.

The question of the interaction of these facilities on their schedules if they were all to be developed concurrently instead of consecutively is also of interest. The level of effort required for the design - something on the order of 300 man years just for the test legs - is such that several engineering organizations would have to be involved in order to bring both the necessary quality and quantity of effort to bear. Assuming site planning and work would have to be coordinated, the effect would be to stretch the schedules slightly, but again the change would most likely be within the built-in error due to the vagaries of the economy, unforeseen changes in emphasis or details, construction procedures, labor performance, etc.

3. POWER SOURCES SURVEY

The ground research facilities investigated in the HYFAC study required varying magnitudes of electrical and mechanical shaft powers. Most of these requirements exceeded current individual facilty and some facility complex power requirements by a considerable margin. In Phase II the problems associated with the power density and maximum power levels of individual components was addressed; and in Volume III, Part 1, the mechanical complexity of obtaining a single high shaft power output by coupling many individual units, in a sometimes limited space, is presented. Aside from these considerations it became apparent in the course of this Phase II effort that the necessary electrical input might not be acquired by straight-forward purchase of power, when the complete facility requirements were considered. Discussions with utility companies and users of large quantities of electrical power led to the development of alternate approaches, reflecting different acquisition and operating costs. This section presents the results of that investigation and the pertinent factors which should be considered in planning the acquisition of over 1,000,000 kW of power for a single facility.

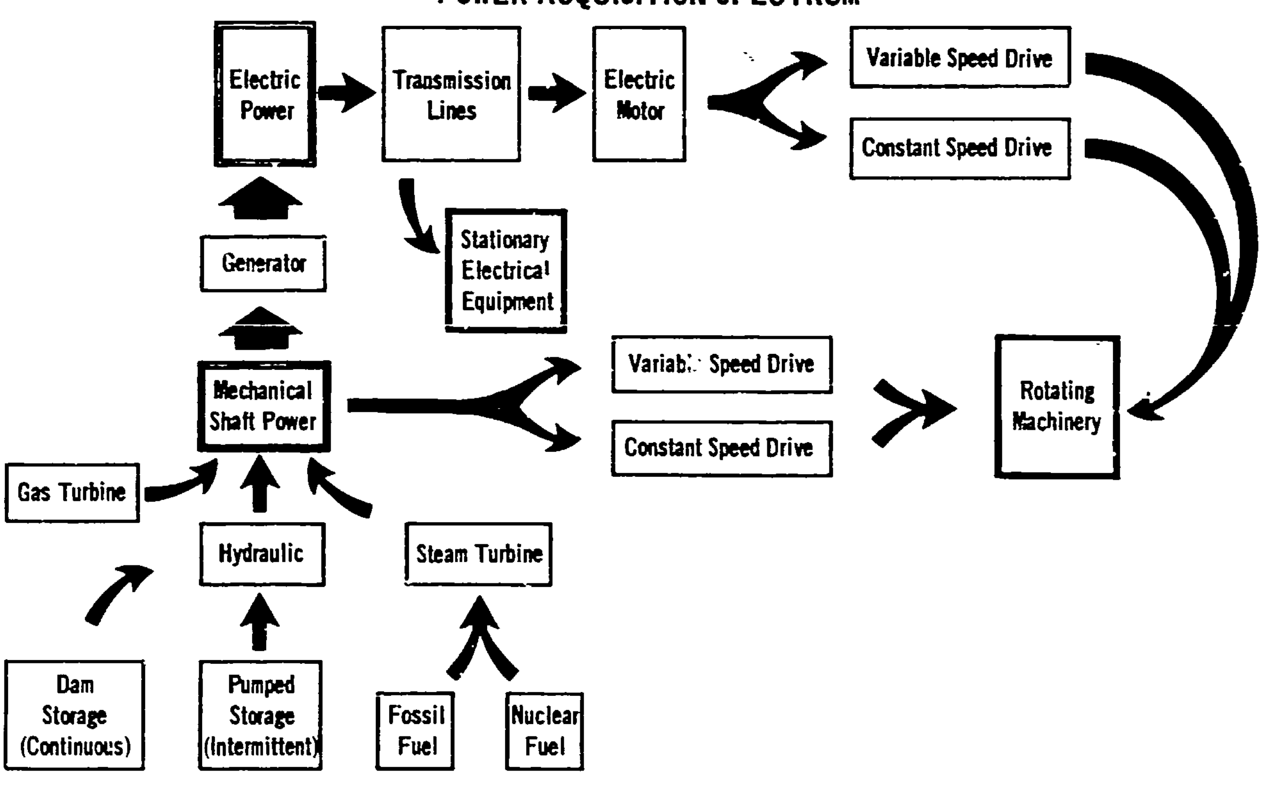
The scope of the power acquisition survey is shown in Figure 3-1. Since the generation of electrical energy normally requires a shaft input, the study considered two primary power inputs, mechanical and electrical.

Although considerable research is currently underway in the development of fossil fuel fired, seeded, magnetohydrodynamic (MHD) generators, no reasonable estimation of acquisition schedules or costs could be made for the quantity of power considered in this investigation. The sole source of electrical energy considered in this investigation is a mechanically driven generator. Because constant speed operation is not satisfactory for all the candidate ground research facilities, the implications of variable speed drives are also assessed.

The large power required could represent a major portion of the power generated by even the very largest electrical networks, and therefore, having the utility reserve a block of power of that magnitude exclusively for the use of a ground research facility would be very costly, if not impossible. The dominating factor is that with the growing demand for electrical power for heating purposes there are now winter peak demands as well as the usual summer demands brought on by the airconditioning requirements. These demands equal or exceed the continuous generating capability in many locales, and for this reason many public and government utilities are installing various intermittent power generating schemes which can be used to meet diurnal or seasonal demands. The general recommendation of the utility companies was that large demands which are not required on a regular, high usage basis should probably be supplied by on-site generating equipment owned by the facility. This factor presents an attractive potential for reducing facility operating costs. If the utilization of the ground research facility permits, the onsite generating plant could be used to supply power to the public utility for peak demands that might not be met by its own equipment or network.

Essentially, three categories of generator input shaft power were examined, as shown in Figure 3-1.

FIGURE 3-1
POWER ACQUISITION SPECTRUM



The gas turbine drives are generally aircraft gas turbine engines modified for constant speed gas generator operation suitable for ground operation with a free turbine stage added at the engine exhaust to provide the shaft output power. Based on existing aircraft gas turbine engines, powers from a few thousand kilowatts to nearly 80,000 kilowatts per machine appear possible.

The steam turbine plants are conventional plants with either a fossil fuel fired boiler or a nuclear reactor as a steam supply. As is the practice in current plant systems, supplemental generating capability represented by gas turbine driven generators can be provided to meet peak demands.

The hydraulic plants are represented by continuously operating hydroelectric generating equipment located at dam sites fed by a tributary system of rivers and watershed runoff. For peaking demands the pumped storage system represents an intermittent operating capacity. In this case, excess generating capacity during off-hours is used to pump water into a storage reservoir. When the peak demands exceed the generating capability, the stored water is permitted to flow through water turbines driving generators, providing additional capacity for a duration consistent with the volume of the reservoir, and reservoir leakage rates.

The following sections discuss the acquisition costs and operating costs for these various systems as well as discussing some of the factors related to the cost of buying electric power from a public utility.

3.1 ELECTRIC POWER SURVEY

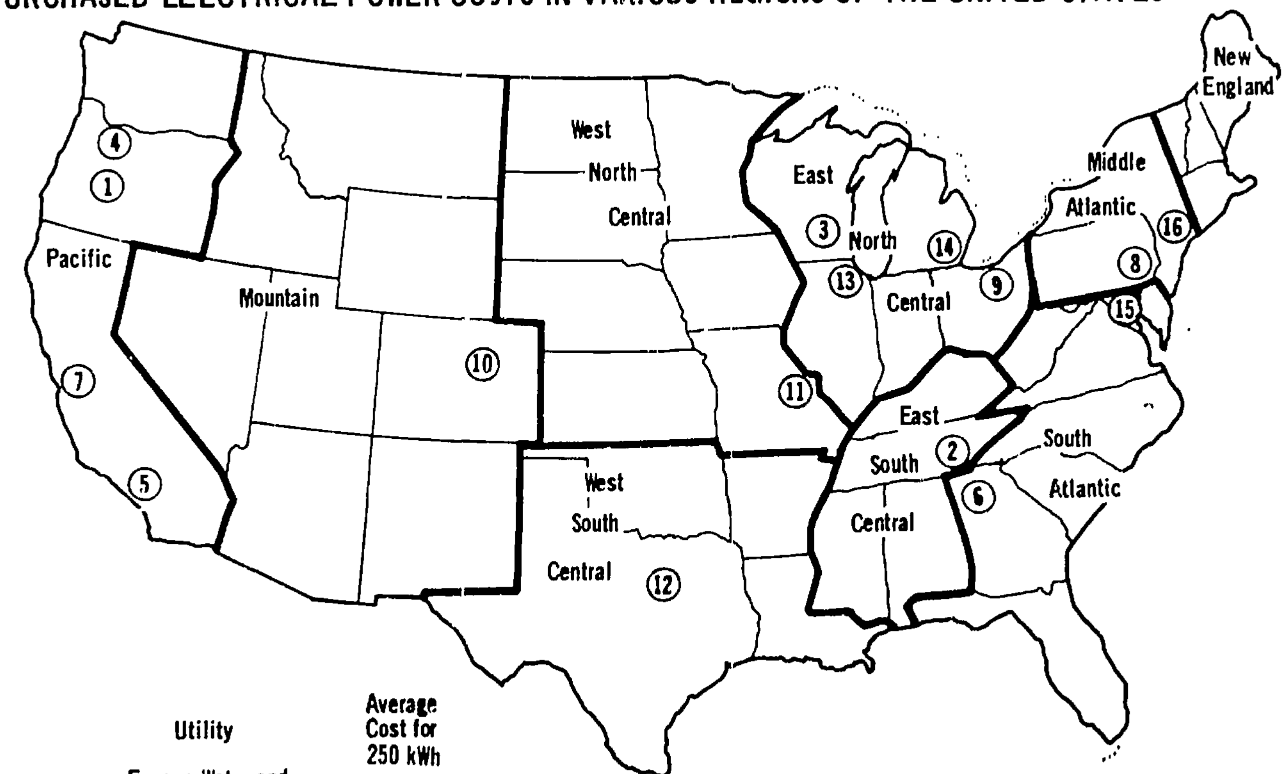
This survey was made to determine the cost of electric power in various regions of the United States and the costs associated with various methods of generating power on-site for HYFAC Ground Research Facilities. A survey of purchased power costs in various regions of the United States is presented in Figure 3-2 and Figure 3-3 shows the factors and considerations involved in establishing these rates.

Some of the differences in power costs shown in Figure 3-2 have to do with geographical population and regulatory factors. The costs of power in the northeast corridor are higher than the other geographical sections of the United States. One factor, for example, which influences the cost is the requirement of exclusive use of underground wiring as in Manhattan, New York, and Washington, D. C. Generally where a major portion of the electrical power is supplied from hydroelectric plants as in the northwest, the power costs are less. Figure 3-2 uses 250 kWh as a basis for establishing costs so that there is no influence of demand charges reflected in the cost figures shown in Figure 3-2.

Figure 3-3 represents an attempt to reflect the many factors which contribute to the final user rates. In the context of the utility company terminology, demand charges represent a payment to the utility for reserving a power capability for an individual user. This is expressed in a maximum power level required in kilowatts. There are many schemes upon which demand charges are based. A few of the more common are:

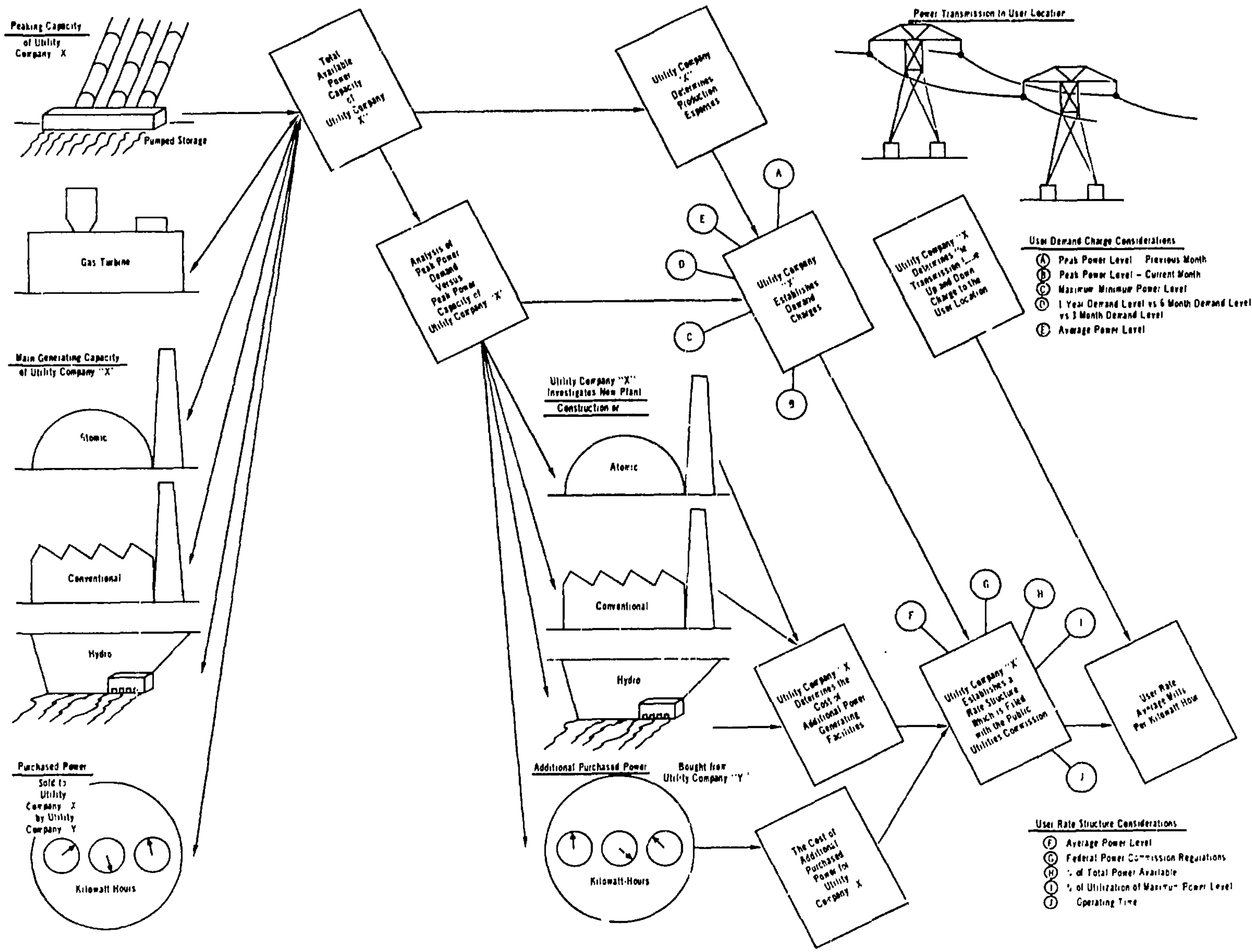
- based on the peak power level demanded in the previous month
- based on the peak power level demanded in the previous month. If this level exceeds current demand level reserved by the utility, a new

FIGURE 3-2
PURCHASED ELECTRICAL POWER COSTS IN VARIOUS REGIONS OF THE UNITED STATES



City	Utility	Average Cost for 250 kWh
1. Eugene, Ore.	Eugene Water and Electric Board	$3.00
2. Chattanooga, Tenn.	Chattanooga Electric Power Board	4.35
3. Madison, Wisc.	Madison Gas and Electric	4.85
4. Portland, Ore.	Portland General Electric	5.35
5. Los Angeles, Calif.	Los Angeles Dept. of Water and Power	5.63
6. Atlanta, Ga.	Georgia Power	5.98
7. San Francisco, Calif.	Pacific Gas and Electric	6.20
8. Philadelphia, Pa.	Philadelphia Electric	6.48
9. Cleveland, Ohio	Cleveland Electric Illuminating	7.04
10. Denver, Colo.	Public Service Colorado	7.12
11. St. Louis, Mo.	Union Electric	7.33
12. Dallas, Tex.	Dallas Power and Light	7.40
13. Chicago, Ill.	Commonwealth Edison	7.57
14. Detroit, Mich.	Detroit Edison	7.74
15. Baltimore, Md.	Baltimore Gas and Electric	8.01
16. New York, N.Y.	Con Edison	10.01

FIGURE 3–3
ELECTRIC UTILITY COMPANY FACTORS AS THEY AFFECT USER RATES



plateau will be established on which charges are based. Under-usage does not reduce charges.

- o based on predetermined maximum and minimum power demand levels. Payments are never less than demand charges for minimum power level reserved.

- o based on demand level over a fixed period of time, such as 3, 6, or 12 months.

Although the basis for establishing the demand charges varies, the payments are required generally on a monthly basis, equal to the demand rate times the peak power reserved.

In general, as the usage of the high power level diminishes and the utility must reserve large blocks of unused power for only occasional usage, the demand charges increase rapidly. A typical example would be a regular user of a large power level who may pay only $.90 to $1.00 per kilowatt demand charge per month, for reserving that power capacity. For the same power demand a user which requires that peak power only occasionally could pay as high as $4.00 to $5.00 per kilowatt.

The basic energy rate is of course based on the total kilowatt-hours delivered to the particular user, and is usually structured so that the larger users pay less per unit energy than small users. This cost is principally based on the cost of producing the electrical energy.

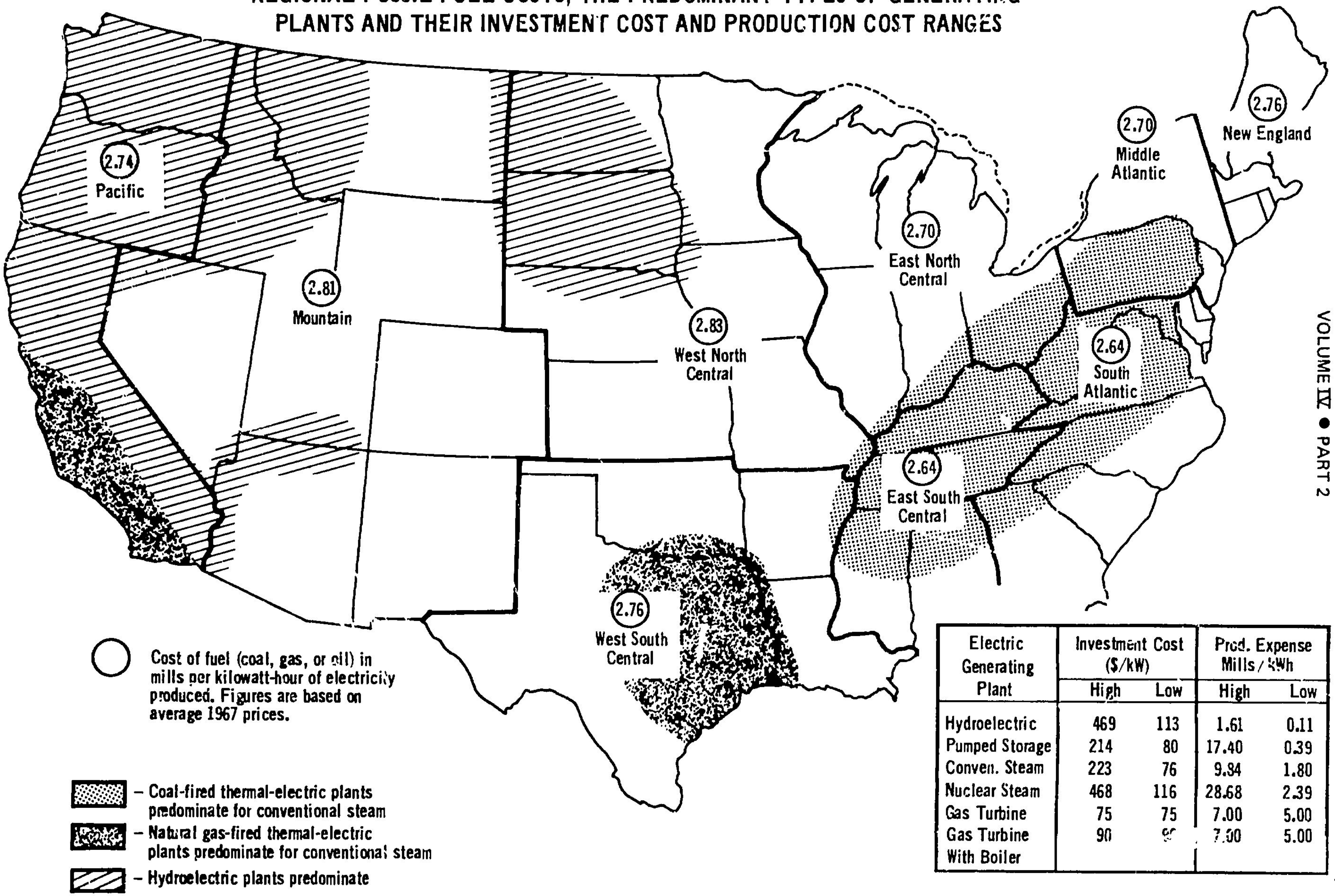
The up-and-down charges represent an additional factor which, although a capital investment for the utility company, is reflected as a monthly charge to the user. These charges represent the cost of running transmission lines to the facility site,amortized over a suitable number of years acceptable to both utility and the user. Should the user terminate operation prior to the end of the amortization period, he would be liable for the unpaid balance of the transmission line costs.

This investigation also examined the investment cost and production expense of generating power by:

- o Hydroelectric Plants
- o Pumped Storage Hydro Plants
- o Conventional Steam Plants
- o Nuclear Steam Plants
- o Gas Turbine Plants

The results of these investigations are summarized in Figure 3-4 and the general trends of investment costs and production expenses as a function of installed generating capacity are shown in Figure 3-5 and Figure 3-6.

FIGURE 3–4
REGIONAL FOSSIL FUEL COSTS, THE PREDOMINANT TYPES OF GENERATING PLANTS AND THEIR INVESTMENT COST AND PRODUCTION COST RANGES



Electric Generating Plant	Investment Cost ($/kW)		Prod. Expense Mills/kWh	
	High	Low	High	Low
Hydroelectric	469	113	1.61	0.11
Pumped Storage	214	80	17.40	0.39
Conven. Steam	223	76	9.34	1.80
Nuclear Steam	468	116	28.68	2.39
Gas Turbine	75	75	7.00	5.00
Gas Turbine With Boiler	90	90	7.00	5.00

FIGURE 3-5
ELECTRIC GENERATING PLANT INVESTMENT COSTS

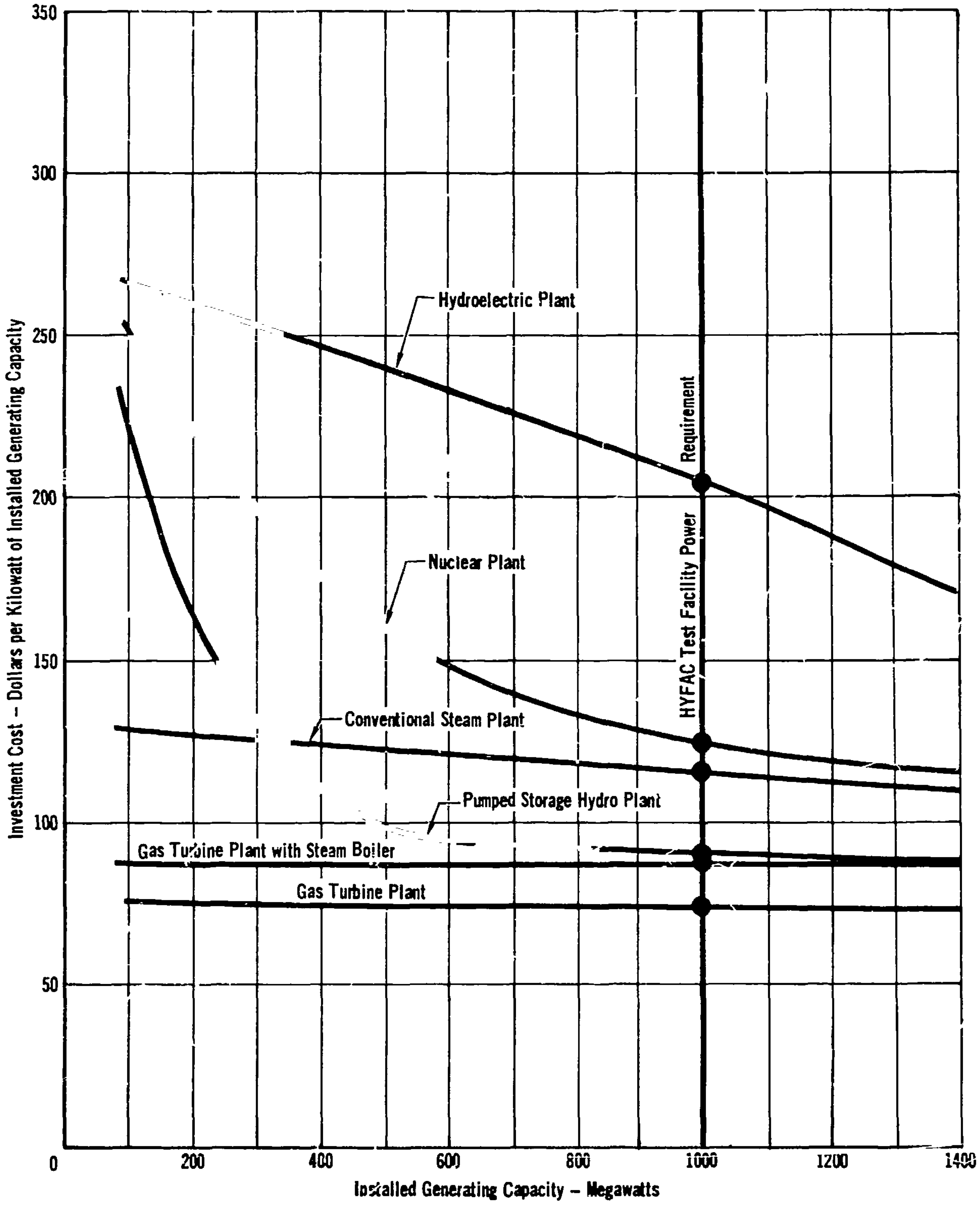


FIGURE 3–6
ELECTRIC GENERATING PLANT PRODUCTION EXPENSE
PER KILOWATT HOUR

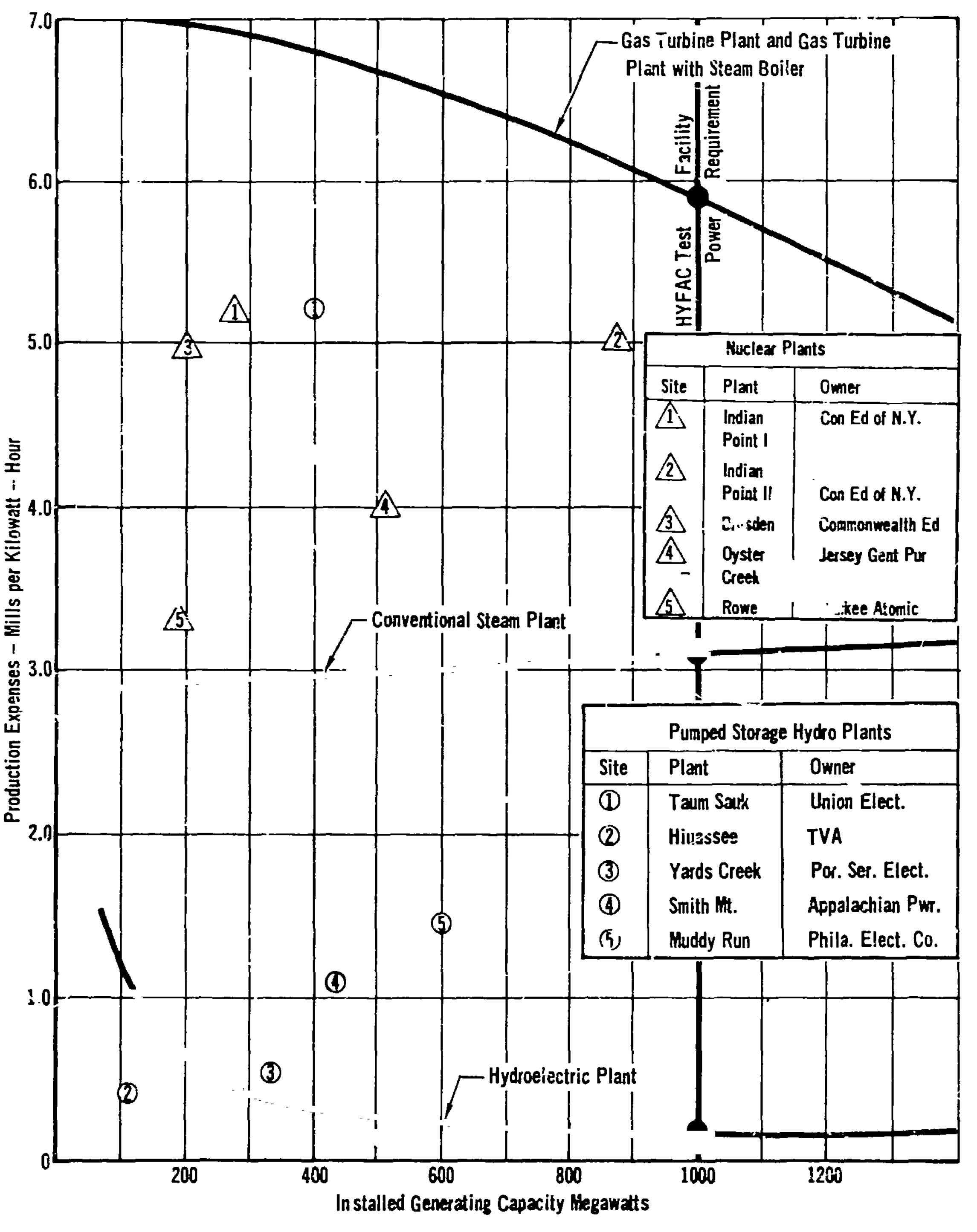


Figure 3-4 shows the range of investment costs and production costs associated with these various methods of generating electric power. The range of numbers reflects the wide variations possible because of local geographical, transportation, and labor factors.

Also indicated are the areas where a particular type of power generating technique dominates.

Figures 3-5 and 3-6 present the specific costs in terms of power output for the five different generating techniques. The relative differences between acquisition and production costs show the trade-offs which are possible between acquisition and operating costs for a particular facility. In general those systems requiring the greatest acquisition costs have the least operating costs. The exception appears to be nuclear power plants where both costs are currently high.

These curves were prepared using data published by the Federal Power Commission, Atomic Energy Commission, NASA, Pratt and Whitney, and General Electric. Specific costs and expenses will, of course, vary from site to site reflecting differences in labor, materials, engineering, site acquisition cost, and fuel. The limited available production expense data for nuclear plants and pumped storage hydro plants precluded the development of production expense curves for these plants. However, some representative production expense points are plotted for these facility types. The fossil fuels used in the production of electric power are coal, natural gas, and residual oil. Coal is the prime fuel in most of the nation, except in the south central natural gas producing area, the Pacific coast region, the upper New England coast and the Florida peninsula. Increasing amounts of western coal are burned each year from New Mexico northward to North Dakota and Montana. Imported water borne residual oil is an important fuel in New England,and in Florida it is the prime fuel. Both natural gas and residual oil are burned by the Pacific coast plants. Natural gas is also burned as a supplemental fuel during the summer months at plants near or on the route of the large natural gas pipelines when there is little or no home heating load on these lines.

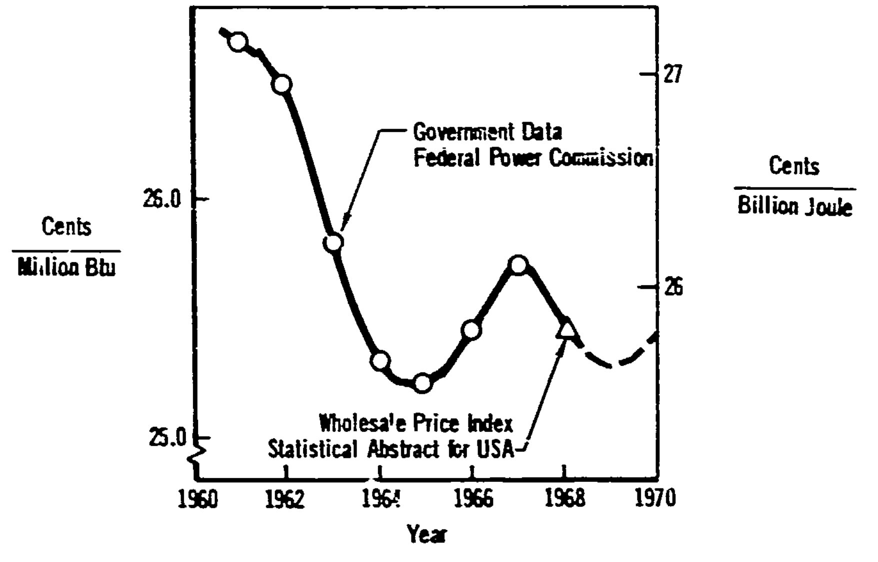
The weighted average fossil fuel costs for the steam-electric generation of the electric utility industry on the "as burned" basis for the years 1960 through 1967 are given in Figure 3-7.

FIGURE 3-7
FOSSIL FUEL COSTS HISTORY

The weighted average fossil fuel costs for the steam-electric generation of the electric utility industry on the "as burned" basis for the years 1960 through 1967 are given in

Fossil Fuel Costs

	1967	1966	1965	1964	1963	1962	1961	1960
	Cents Per Million Btu (As Burned)							
Coal	25.2	24.7	24.4	24.5	25.0	25.6	25.8	26.0
Gas	24.7	25.0	25.0	25.4	25.5	26.4	25.1	23.8
Oil	32.2	32.4	33.1	32.7	33.5	34.5	35.4	34.5
Weighted Average	25.7	25.4	25.2	25.3	25.8	26.5	26.7	26.2



A study of hydroelectric generating plants revealed that of the major drainages, the North Pacific has the largest amount of both developed and undeveloped hydroelectric capacity, accounting for about one-third of the total United States capacity (Figure 3-8). Almost two thirds of the capacity under construction in 1968 was also in the North Pacific drainage.

Over the years, hydroelectric plants have provided a substantial but declining portion of the nation's electric power supply. In 1968 they accounted for 17% of the total electric production and, despite a substantial hydroelectric construction plant rate, the increasing demands for power have exceeded the availability of economical hydroelectric sites in most parts of the country. Those hydroelectric plants designed in recent years have increasingly been designed for peak load operation. With the trend toward large hydroelectric power installations for peaking purposes, there is also a trend toward larger generator units. The planned enlargement of Grand Coulee will use 600,000 kilowatt generator units. In general, both the investment and operating costs per kilowatt of installed capacity for the powerhouse and equipment can be decreased through the installation of larger sized units.

Investment costs per kilowatt for recently constructed hydroelectric plants spread over a wide range from plant to plant - \$113 to \$424 for non-federal plants and \$144 to \$469 for federal plants. Differences in investment cost per kilowatt reflect not only changes in labor, materials, engineering, and other factors in construction costs but also the wide variations in type, size, and location of projects, cost of land and relocation of existing roads and structures.

Annual system hydro production expenses per kilowatt-hour ranged from 0.11 mill in the largest of the non-federal hydroelectric systems to 1.61 mills in another non-federal system. For the non-federal systems, the unit costs in 1967 averaged 0.50 mill per kilowatt-hour (0.32 mill for operation and 0.18 mill for maintenance). For the TVA the 1967 average unit cost was 0.61 mill per kilowatt-hour (0.41 mill for operation and 0.20 mill for maintenance). Production expenses per kilowatt-hour are substantially less in hydroelectric than in thermal-electric plants principally because there are no fuel costs.

Comparing HYFAC Facility power requirements with site capacities (Figure 3-9) showed that in many cases the total power required for a ground test facility exceeded the capacity of a site.

Pumped storage hydroelectric generating plants are of two general types: (1) those in which pumped storage facilities are constructed with or added to a conventional hydroplant, and (2) those which are exclusively pumped storage and generate power by recirculating the water between an upper and a lower reservoir. These plants are used primarily as peaking plants and are selected on the basis of low first cost and the ability to convert low cost off-peak pumping energy to high values of peak power.

Pumped storage projects are usually more economically developed at sites having high heads. Costs of development depend largely upon site topography and geological conditions. Between 1953 and 1959, the Union Electric Company of St. Louis investigated approximately nine sites with regard to geological conditions, pumping cycle, upper and lower reservoir capacities, and transmission line distance before

FIGURE 3-8
CONVENTIONAL HYDROELECTRIC POWER, JANUARY 1, 1968, DEVELOPED AND UNDEVELOPED

By Major Drainages

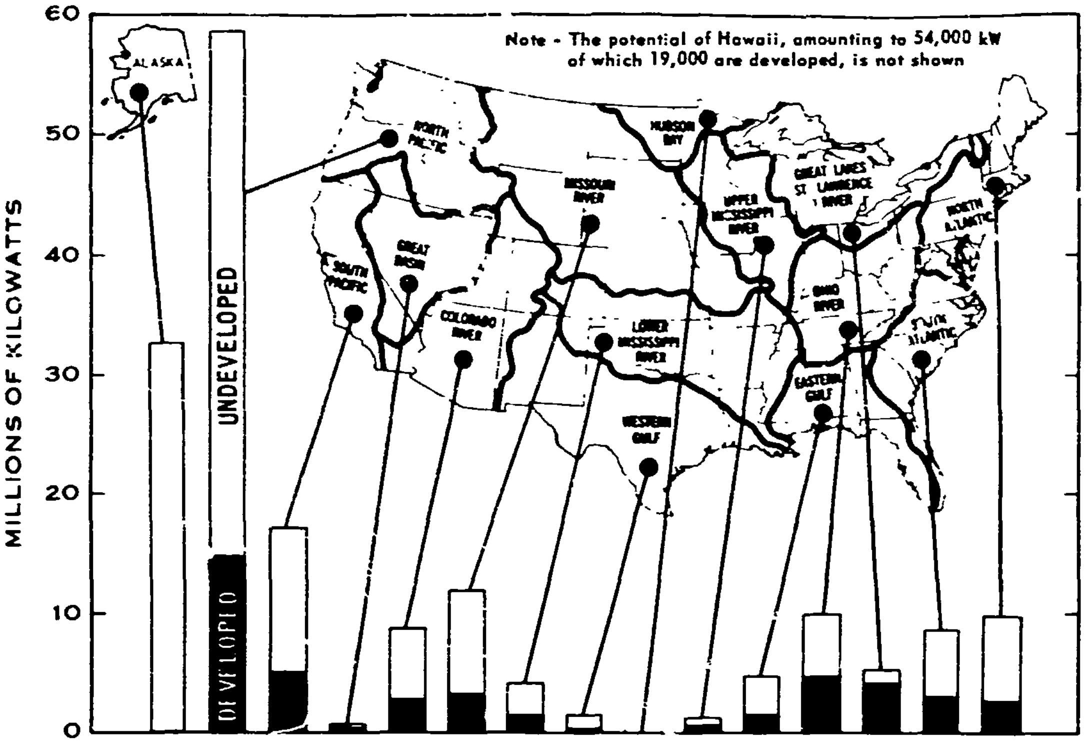


CHART 1

By Geographic Divisions

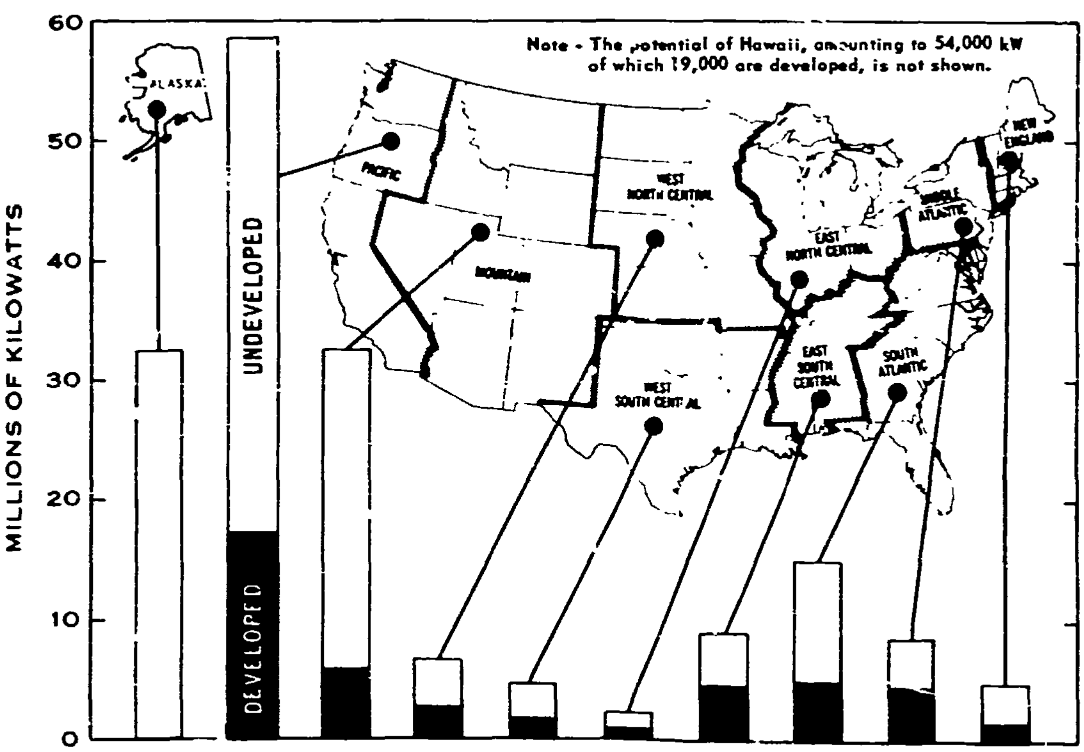
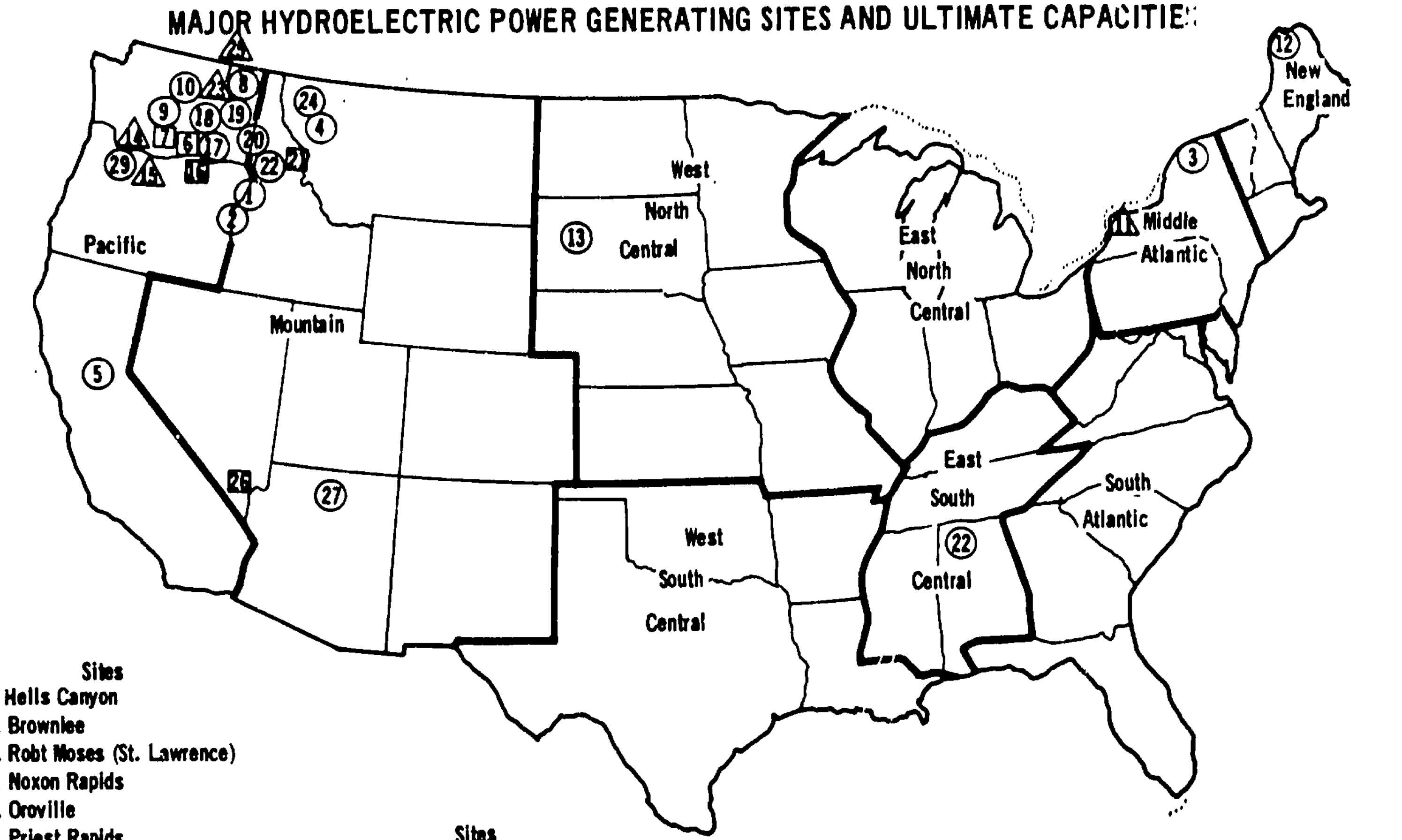


CHART 2

FIGURE 3–9

MAJOR HYDROELECTRIC POWER GENERATING SITES AND ULTIMATE CAPACITIES



Sites
1. Hells Canyon
2. Brownlee
3. Robt Moses (St. Lawrence)
4. Noxon Rapids
5. Oroville
6. Priest Rapids
7. Wanapum
8. Boundary
9. Rocky Reach
10. Wells
11. Robt Moses (Niagara)
12. Dickey
13. Oahe
14. The Dalles
15. John Day

Sites
16. McNary
17. Ice Harbor
18. Lower Monumental
19. Little Goose
20. Lower Granite
21. Dworshak
22. Asotin
23. Chief Joseph
24. Libby

Sites
25. Grand Coulee
26. Hoover
27. Glen Canyon
28. Wilson
29. Bonneville

○ Ultimate Generating Capacity Between 500 MW and 1000 MW
□ Ultimate Generating Capacity Between 1000 MW and 1500 MW
△ Ultimate Generating Capacity in Excess of 1500 MW

selecting and developing the present Taum Sauk site. Reservoirs, dams, waterways (tunnels), pump-turbine and motor-generator equipment represented approximately 70% to 75% of the total facility cost. The limited information available on the actual and estimated investment costs for recently constructed and proposed developments indicate that economically attractive projects will generally have a cost range of $70 to $125 per kilowatt.

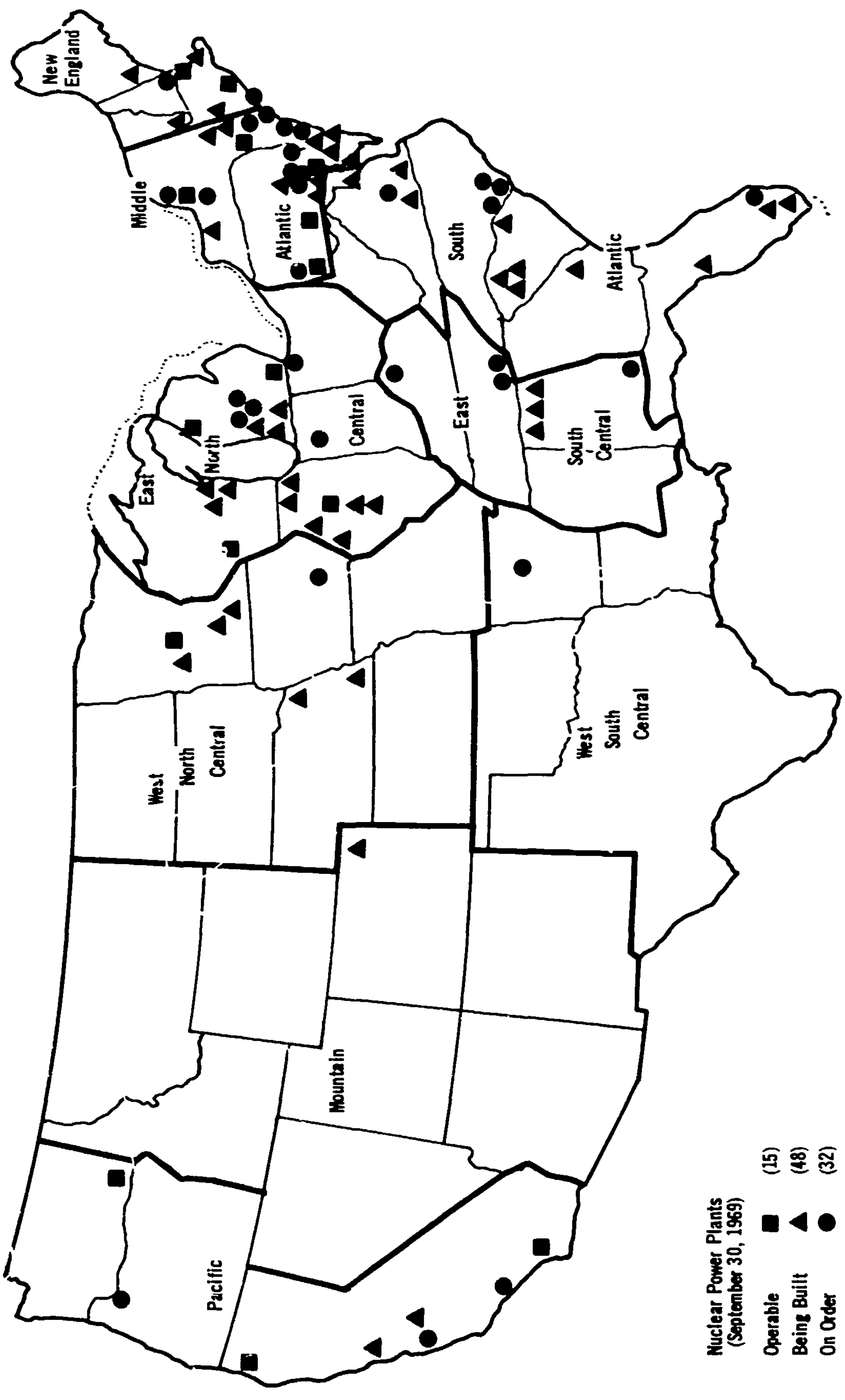
These power projects may be designed for either a daily or a weekly cycle of operation. The latter affords more flexibility in use, however, because of the ability to do a substantial portion of the pumping during weekends. For every two kilowatt-hours of energy generated, approximately three kilowatt-hours of energy are required for pumping. Therefore, an important factor in considering the economic justification of a pumped storage project is an economical source of pumping energy. Normally, pumping energy is provided by steam-electric plants.

Conventional steam-electric power plant design and construction advances made during the past two decades are attributable to efforts to design, build, and operate the most economical and most reliable generating plants. Larger generating units have considerably lowered investment costs per kilowatt of capacity and have reduced production expenses per kilowatt-hour. The use of outdoor or semioutdoor and unit type (a single boiler for each turbine-generator) construction has also reduced investment costs. Higher steam temperatures and pressures, and modern reheat cycles have resulted in better heat rates and consequently lower kilowatt-hour fuel costs.

However, air pollution, the thermal effects on sources of cooling water, and the physical appearance of the generating facilities have emerged as major issues in the cost of steam electric power plants. Because of undesirable biochemical effects of temperature increases on sources of cooling water supply, cooling towers are now being included in plant designs at sites which in the past would have been considered well suited for "once through" cooling systems. Particulate matter and oxides of sulfur, the principal air pollutants associated with conventional steam-electric plants, have brought about a growing demand for very high efficiency (99%) electrostatic precipitators. The installation of higher boiler stacks to obtain dispersion of oxides of sulfur and the use of low sulfur fuel are both increasing. These factors tend to offset some of the savings brought about by the technological advances in power plant design over the last twenty years. Fuel costs account for 79% of the total production expenses. The principal component of the remaining 21% is labor cost, including supervision and engineering. Plant operating supplies including lubricants, chemicals, miscellaneous materials, office and other incidental expenses and maintenance renewal parts and materials make up the balance of the 21%. An increasing number of mine-mouth plants are being constructed. These plants provide a substantial reduction in fuel costs by eliminating transportation costs and to some extent storage costs.

The phenomenal growth of nuclear power since 1960 can be attributed to a considerable extent to the trend toward large-size power generating units on large-scale power systems and to the fact that the utility industry accepted nuclear power as safe, reliable, and as the most economic means of meeting a sizable portion of its new power requirements. On 30 September 1969, a total of fifteen nuclear power plants were in operation with a total generating capacity of 3,851,700 kilowatts (Figure 3-10) the largest of these is the 3,195,000 kilowatt Browns Ferry

FIGURE 3-10
NUCLEAR POWER PLANTS IN THE UNITED STATES



Plant of the TVA which is scheduled for completion by 1972. Soaring costs and construction delays have, however, triggered a few atomic-plant cancellations, and in some cases, utilities are instead ordering fossil fuel plants.

There is also increasing concern over safety, radioactivity, and thermal pollution. Property owners near Commonwealth Edison's Zion nuclear project on the shores of Lake Michigan have filed suit against the utility claiming the nuclear plant would heat the water too much and that radioactive waste would be introduced into the lake. The Metropolitan Sanitary District of Chicago has filed a suit against the utility claiming the plant would endanger the city's drinking water. During field hydrostatic testing of the Oyster Creek, N. J. installation, a leak was detected in the reactor pressure vessel. Detailed examination revealed defects in the welds joining the stub tubes to the control rod housing and construction has been delayed approximately two years. Construction of the Ravenswood Plant had to be abandoned by Consolidated Edison due to fierce public opposition.

However, as engineering problems are solved and technological advances such as the breeder reactor become practical, the cost of nuclear plant construction is expected to stabilize at an average of $150 per kilowatt of installed capacity and operating costs are expected to decline to about 4 mills per kilowatt-hour.

The best prospects for nuclear power lie in those regions where the cost of fossil fuel is above average. Most major nuclear plants now being built or planned (Figure 3-10) are in the Middle Atlantic and New England regions of the United States where coal transportation costs are high.

The general conclusion reached was that for the ground research facilities the power demand is not uniform and in fact could vary considerably in terms of demand and usage. Any of the steam generating concepts are best for continuous operation and slowly changing loads. The bringing on-line of a very large steam plant to near maximum power from a low power idle condition would probably require hours, and from a cold, unfired condition, one or two days. Since hydroelectric power is restricted geographically, it appeared that the best source of obtaining large power levels on intermittent, variable power level basis was the gas turbine engine drive. These do not have the maintenance required during non usage that large steam plants have, require virtually no warm-up, and can be brought up to full power in a matter of a few minutes. Substantially less investment in real estate, building, and equipment are required compared to large steam plants.

On this basis gas, turbine plants appear to offer the best solution to "on-site" power generating requirements. There are two types of gas turbine generating units presently in use in the United States, primarily for peak load service. One employs the industrial type gas turbine that is also used by industry for mechanical drive purposes. These units vary in size from about ten to a maximum of 40 megawatts. The other uses the aircraft jet engine for the compressor-combustor component. Sizes range from 12.5 to 17.5 megawatt units driven by a single jet engine to the quite large 115 to 160 megawatt unit which requires eight jet engines and four turbines or expanders for a single generator.

The total United States installed capacity in gas-turbine generating units at the end of 1967 was 3300 megawatts. By 1970 this capacity had increased to 10,000 megawatts. The ease of obtaining large increments of power without having to consider network loads, energy absorption capacity in the event of failure, operational times restricted to off-peak hours, and demand charges make gas turbine generators located "on-site" very attractive. If natural gas fuel could be used, it is estimated that power could be had for 5 to 7 mills per kilowatt hour including fuel, maintenance, operators, and amortization.

A variant of the gas turbine generating plant is an optimized combination of a gas turbine, an exhaust heat recovery steam generator and a steam turbine for generator drive. In the gas turbine's combustion chambers, fuel is mixed with compressed air from the compressor and burned. The resulting hot gas expands through the gas turbines, which drives the compressor and the gas turbine generators. Hot exhaust from the gas turbine is heated by supplemental fuel before entering boilers where steam is generated for the steam turbine. There are four turbines required for each plant. Any one of the four gas turbine boiler combinations will supply sufficient steam to operate the plant at a minimum combined cycle load of approximately 60,000 kW. For additional output up to the maximum output of the plant, additional gas turbine boiler combinations are put on the line.

To minimize modification to the basic aircraft engine, the ground installation utilizes the engine as a gas generator driving a free turbine as shown in Figure 3-11. The free turbine could be a specially designed unit or a commercial unit such as the Worthington ER-244 twin exhaust expander turbine. Using such installations, outputs from 20,000 to 220,000 shaft horsepower are available in single or dual units.

Data from Pratt and Whitney Aircraft shows a total of 464 units delivered with a total of 1,192,310 operational hours accumulated. Some of the units consist of eight FT4A engines driving four twin expander turbines on a single shaft. Considering the 28,000 to 30,000 hour overhaul life of these engines, this is a very feasible prime mover.

Fuels which can be used include Jet A, Jet B, Naptha, N° 2 heating oil, and N° 2 Diesel Oil. When operating on natural gas, a supply pressure of 3000 psi (2070 N/cm^2) is required because of the engine's compression ratio. It is possible to operate the unit on liquid or gaseous fuels and to switch fuels under load using an automatic dual fuel system.

As presented in Volume III, Part 2, a possible method to attain single unit power levels greater than those available from current jet engines would be to utilize the SST engine, the General Electric GE4/J5P, as a hot gas source for a free turbine. This engine has the largest mass flow for a turbojet engine, 633 lb/sec (287 kg/sec) available today. This engine attached to a free turbine may be capable of delivering up to 80,000 kW of shaft power. This would minimize the number of engines required to achieve a given power level.

The acquisition costs have been shown in Figure 3-12 for a number of available gas turbine systems suitable for ground installations. One system, the General Electric Series 7000 system, is the largest of a group of direct drive turboshaft specifically designed for ground installations. Their design, size, and weight differ considerably from the aircraft turbojets. The Pratt-Whitney ground power engines are based on the JT3C and JT4A twin spool aircraft turbojets. With a

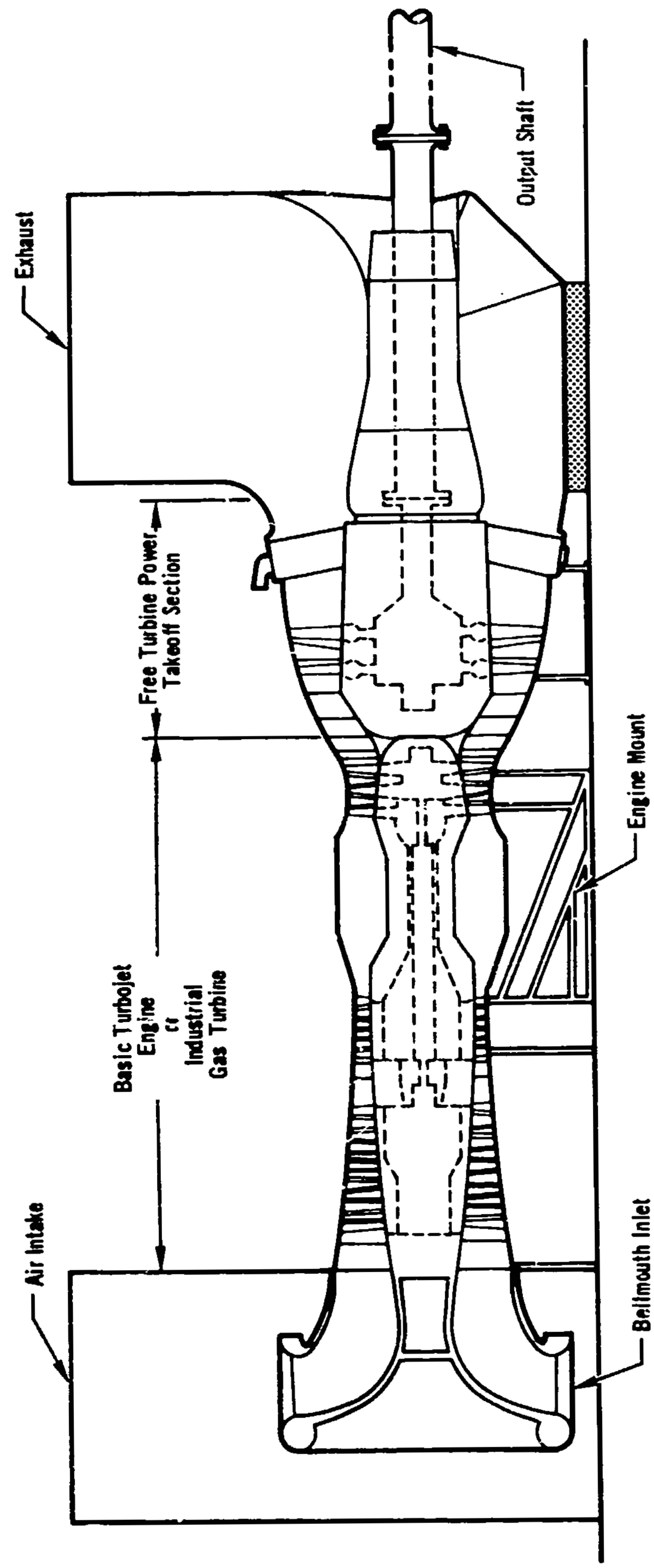
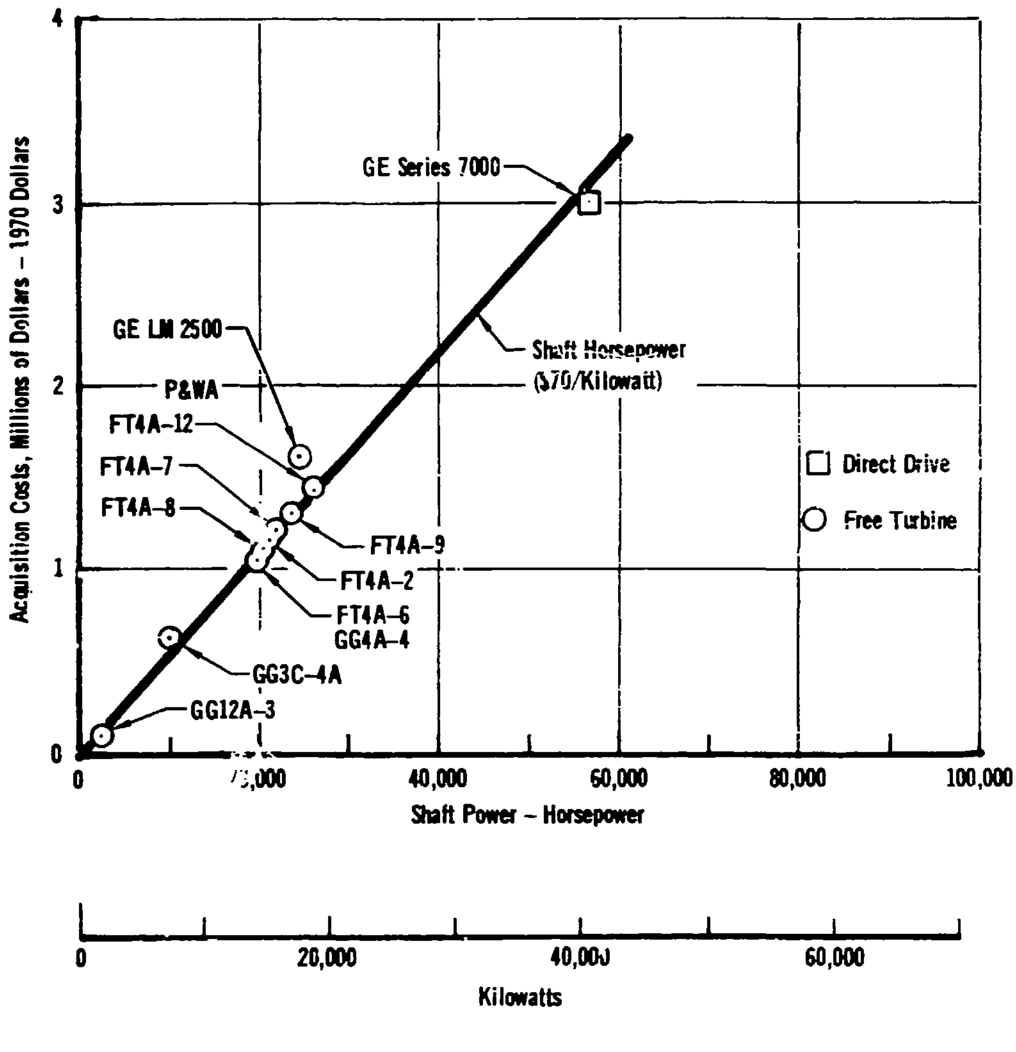


FIGURE 3-11
REPRESENTATIVE GROUND INSTALLATION OF AIRCRAFT TURBOJET ENGINE TO PROVIDE SHAFT POWER SOURCE, SINGLE ENGINE INSTALLATION

FIGURE 3-12
GAS TURBINE PRIME MOVER ACQUISITION COST, PRESENT ACTUAL COSTS



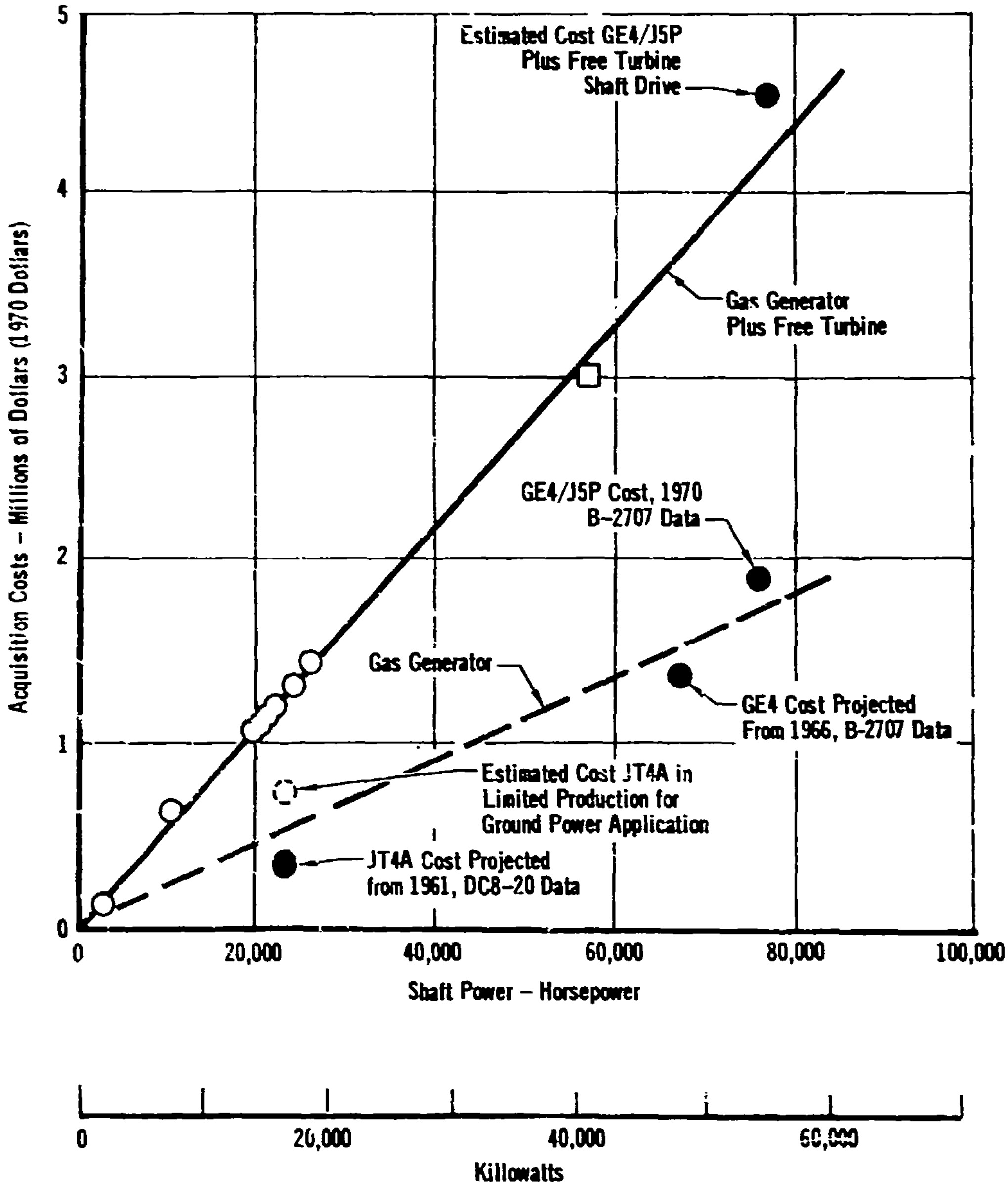
compression ratio of about 12, this can provide about 110 shp per pound per second mass flow (183 $\frac{\text{kW-sec}}{\text{kg}}$). The General Electric LM2500 system is based on the core engine of the TF-39 turbofan engine. Removal of the high by-pass fan and having a compressor with a 29 to 1 pressure ratio provides an output of about 160 $\frac{\text{shp-sec}}{\text{lb}}$ (263 $\frac{\text{kW-sec}}{\text{kg}}$). The average cost for gas turbines appears to be about 52 dollars per shaft horsepower ($70/kW).

Figure 3-13 presents an extrapolation of existing data to predict an acquisition cost for a ground power unit based on the GE4/J5P. This straight turbojet, with a pressure ratio of 12, was estimated to be capable of delivering 75,000 shp (56,000 kW) using the performance of the G.E. Series 7000 engine as a base.

FIGURE 3–13
GAS TURBINE PRIME MOVER ACQUISITION COSTS – PROJECTED COSTS

Power Conversion, Shaft Power/Engine Mass Flow

$100 \frac{hp}{(lb/sec)} \left(163 \frac{Watt}{kg/sec}\right)$



3.2 MECHANICAL DRIVE PLANT STUDY

This section is a derivative of the Electrical Power Survey, Section 3.1. Consequently, the discussions in Section 3.1 are also applicable to this area.

The investment costs and production expenses for mechanical drive plants are presented in Figure 3-14. Variations of these costs with power is shown in Figure 3-15. These costs were prepared from data in Figures 3-5 and 3-6 by deleting costs associated with electrical generators. The cost of power transmission gearing and shafting is not included as this is dependent on the physical arrangement of the installation. Specific costs and expenses will, of course, vary from site to site reflecting differences in labor, materials, engineering, site acquisition cost, and fuel.

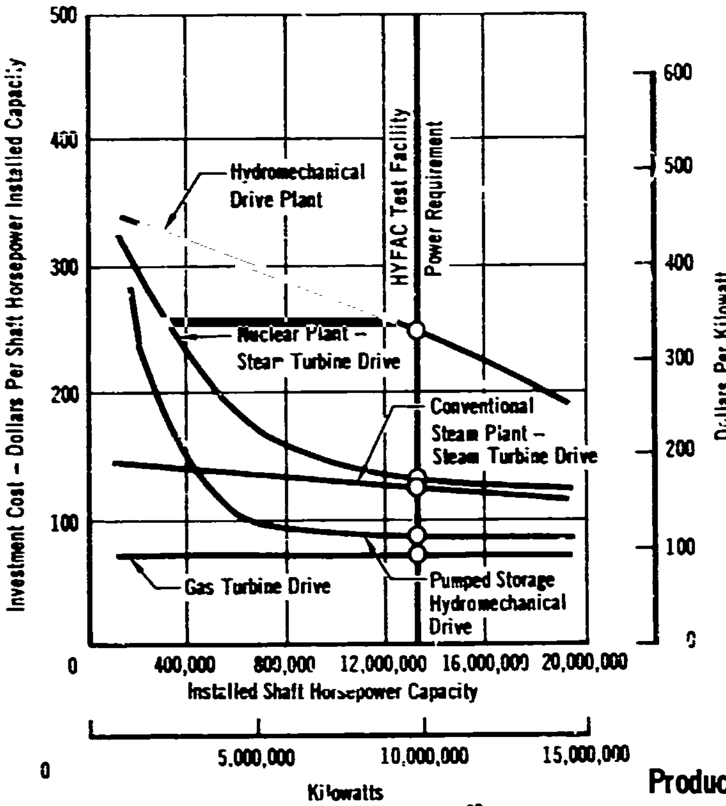
FIGURE 3-14
MECHANICAL DRIVE PLANT INVESTMENT COSTS AND PRODUCTION EXPENSES

MECHANICAL DRIVE PLANT	INVESTMENT COST				PROD. EXPENSE			
	$/shp		$/kW		MILLS/hph		MILLS/kwh	
	HIGH	LOW	HIGH	LOW	HIGH	LOW	HIGH	LOW
HYDROELECTRIC	327	62	440	83	1.20	0.082	1.61	0.110
PUMPED STORAGE	137	40	184	5[illegible]	13.96	0.29	18.80	0.39
CONVENTIONAL STEAM	144	3[illegible]	194	46	7.33	1.34	9.90	1.80
NUCLEAR STEAM	327	64	440	86	21.40	1.78	28.80	2.39
GAS TURBINE	53	47	71	63	5.21	3.72	7.00	5.00

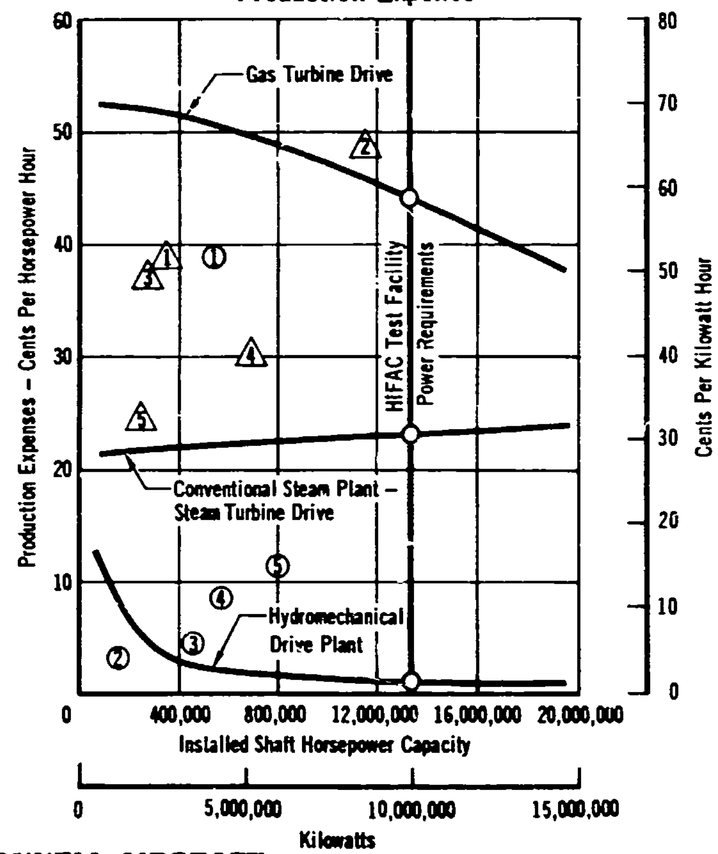
Based on the discussions in Section 3.1, gas turbines will be considered for ground facility operations where mechanical drives are required. The engines are either industrial gas turbines or adaptations of aircraft turbojets and have been used for a number of years for ground installations. These turbines can provide large increments of power without having to consider network loads, energy absorption capacities in the event of failure, and the demand charge of a utility company. Off-peak hour operation restrictions are also eliminated by the use of gas turbines.

FIGURE 3-15
MECHANICAL DRIVE SYSTEM COSTS

Plant Investment Costs



Production Expense



Nuclear Plants		
Site	Plant	Owner
1	Indian Point I	ConEd of N.Y.
2	Indian Point II	ConEd of N.Y.
3	Dresden	Commonwealth Ed
4	Oyster Creek	Jersey Cent. Pwr
5	Rowe	Yankee Atomic

Pumped Storage Hydro Plants		
Site	Plant	Owner
1	Taum Sauk	Union Electric
2	Hiwassee	TVA
3	Yards Creek	Pub. Serv. Electric
4	Smith Mt.	Appalachian Power
5	Muddy Run	Phila. Electric Co.

3.3 VARIABLE SPEED DRIVE SYSTEMS

The gas turbine engine drive coupled with a free turbine is a rather simple method to obtain variable speed outputs. The output shaft speed can be coupled through a fuel control system to the gas generator and speed is just a function of load and gas generator output.

For electric motor drives, however, variable speed drives for very large powers are not as simple, nor as responsive as the gas turbine.

This section identifies the available methods of providing variable speed drive systems for heavy equipment. A summary of these methods, their characteristics, costs, and applications is presented in Figure 3-16. Maintenance costs for the rotating electrical equipment can be estimated as approximately one percent of the first cost per year. Gas turbine maintenance costs are 0.15 mills per horsepower-hour of operation and include a hot gas path inspection every 9000 hours and a complete major inspection and service after every 28,000 hours of operation. Fuel and stationary operating engineer labor expenses for gas turbine prime movers amount to an additional 4.1 mills per horsepower-hours.

The variable speed drive concepts presented are:

- o DC adjustable voltage
- o Wound rotor motor and liquid rheostat control
- o Wound rotor motor and DC adjustable voltage
- o Modified Kramer
- o Induction frequency converter
- o Leblanc system
- o Adjustable frequency generation
- o Variable speed gas turbine
- o Variable speed gas turbine and DC motor
- o Synchronous motor and slip coupling

FIGURE 3-16
COMPARISON OF VARIABLE SPEED DRIVE SYSTEMS

Type of Drive	Range of Speed	Accuracy of Speed	Overall Efficiency	Drive Cost Per hp (per kW)	Best Application	Remarks
DC adjustable voltage	10-1	Good	Fair	$120 (160)	Small capacity with moderate speed requirements	
Wound rotor motor and liquid rheostat control	3-1	Fair	Poor	$60 (80)	Where momentary deviations in speed are permissible	
Wound rotor motor and DC adjustable voltage	10-1	Good	Poor	$75 (100)	Where efficiency is not important	
Modified Kramer	10-1	Good	High	$150 (200)	Where large capacity is required	Certain rotating equipment items are not readily available
Induction frequency converter	10-1	Good	Good	$150 (200)	Medium capacity drives	Certain rotating equipment items are not readily available
Leblanc system	6-1	Good	Good	$150 (200)	Small capacity drives	Certain rotating equipment items are not readily available
Adjustable frequency generation	6-1	Good	High	$130 (175)	Very large drives	Cost based on simple cycle gas turbine
Variable speed industrial gas turbine	5-1	Good	High	$80 (107)	Very large drives	Cost based on simple cycle gas turbine
Variable speed industrial gas turbine and DC motor	10-1	Good	High	$120 (160)	Very large drives	Cost based on simple cycle gas turbine
Sync. motor and slip coupling	10-1	Good	Poor	$75 (100)	Medium capacity drives	

3.4 POWER SOURCES SUMMARY - INFORMATION SOURCES

The manufacturers and utility companies supplied a significant amount of data on the performance, operation, maintenance, and cost factors associated with the application of various types of power systems. Acknowledged for their efforts in providing a realistic base for the data presented in this section are:

Jacksonville Water and Light Department, Jacksonville, Illinois

Union Electric Company, St. Louis, Missouri

United States Army Corps of Engineers, Missouri River Division, Omaha, Nebraska

Pratt and Whitney Aircraft Company, Turbo-Power and Marine Department

General Electric Company, Marine and Defense Facilities Sales Division

Niagara Mohawk Power Company

New York State Gas and Electric Corporation

American Electric Power System

Georgia Power Company

The data obtained from the current literature concerning the application of different energy sources to large power demands covered a wide spectrum of techniques and applications. The articles which contributed to this section are listed in the following:

Federal Power Commission, Hydroelectric Plant Construction Cost and Annual Production Expenses - Combined Tenth and Eleventh Annual Supplements 1966 and 1967. March 1969.

Federal Power Commission, Steam-Electric Plant Construction Cost and Annual Production Expenses - Twentieth Annual Supplement 1967, November 1968.

Federal Power Commission, Hydroelectric Power Resources of the United States Developed and Undeveloped, January 1968.

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Fortune, The Growing Market for Nuclear KW, July 1963.

Fortune, "We're The Most Enterprising Utility In This Country", May 1964.

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Fortune, Products and Processess, March 1965.

Fortune, An Atomic Bomb In The Land of Coal, September 1966.

Fortune, Nuclear Power Goes "Critical", March 1967.

Fortune, The Next Step Is The Breeder Reactor, March 1967.

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Power Engineering Magazine, Union Electric's Team Taum Sauk Pumped-Storage Hydro Plant.

Compressed Air Magazine, Manapouri Dam, February 1970.

Electrical World, Power Giant Comes of Age In Labrador, February 16, 1970.

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Aerospace Technology, FBRS To Get $800 Million Over Five Years, March 11, 1968.

Science, Nuclear Power-Rosy Optimisim and Harsh Reality, July 12, 1968.

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Sears, F. W. and Zemansky, M. W., College Physics, Part I, Third Edition, 1960.

Davis, C. V., Handbook of Applied Hydraulics, Second Edition, 1952.

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Hunt, W. T., and Stein, R., -Static Electromagnetic Devices, 1963.

Westinghouse Engineer, Big Winds for Model Planes, March 1948.

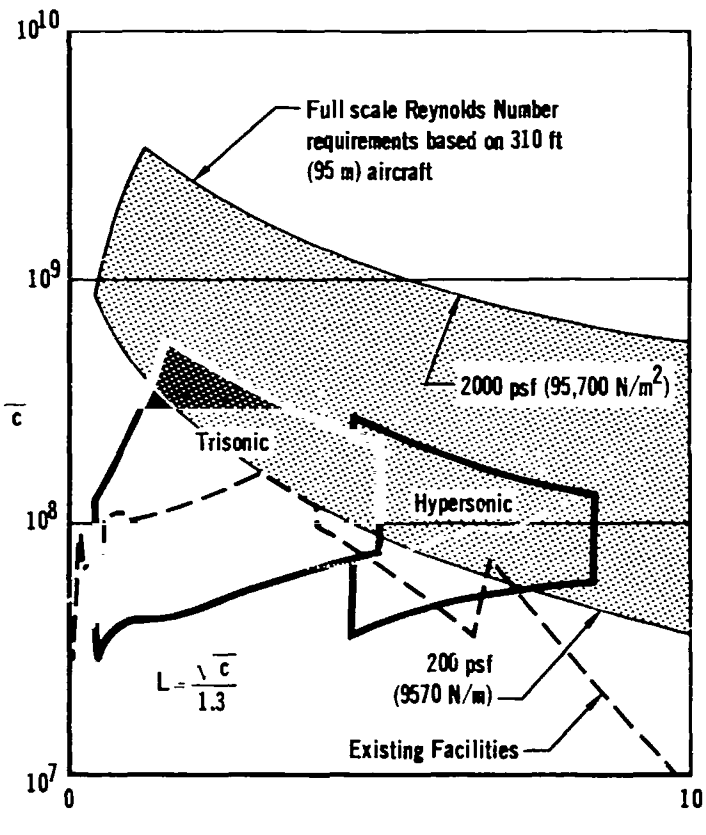
Electrical Engineering, - Variable Speed Drive For United States Army Air Corps Wind Tunnel at Wright Field, Dayton, Ohio
AIEE Transactions, Vol. 61 No. 3 March 1942.

4. POLYSONIC BLOWDOWN WIND TUNNEL (GD20)

GD20 is an intermittent wind tunnel operating in the Mach number range from 0.5 to 8.5. Two independent test legs are employed. The trisonic test leg has a test section 16 x 16 ft (4.9 x 4.9 m) and can operate up to Mach 5.0. The hypersonic test leg operates between Mach 4.5 and 8.5 and has a test section 12 x 12 ft (3.7 x 3.7 m).

In Phase II, size and pressure tradeoffs were made to determine their effect on facility component specifications and costs. It was found that the baseline facility definition, which is the smallest facility size able to produce the desired Reynolds number (one-fifth of the maximum full-scale values of the HYFAC operational vehicles), provided a significant increase in research capability as well as having the best research return per invested dollars. The baseline definition was therefore chosen to be carried forward into Phase III essentially unchanged in its capabilities.

The performance envelope for GD20, in terms of the Reynolds number simulation capability, is shown below. The Reynolds number capability is based on providing one-fifth the flight Reynolds number for a 310 foot (95 meter) long aircraft flying a 2000 psf (95700 N/m^2) dynamic pressure flight path. For smaller vehicles, and lesser dynamic pressures, GD20 provides greater than 20% Reynolds number simulation level.



The shaded area represents the HYFAC potential operational hypersonic aircraft flight envelope, developed in Volume II, for a 310 ft (95 meter) long aircraft. The broken line represents the maximum capability for a composite of existing facilities. The reference length on which the Reynolds number is based is the square root of the wind tunnel test section cross sectional area, defined in Phase I as being equal to 1.3 times the aircraft or model length. This sizing criteria was selected because it provides a working tolerance to increase the operational flexibility of the gasdynamic facilities. A model sized for the trisonic leg would be about 12.3 feet (3.75 m) long. If only one model were provided, this model could be accommodated in the hypersonic leg test section without degradation of performance or angle of attack range. With this large model size, the Reynolds number capability in the hypersonic test leg would be 34% greater than shown in the previous sketch.

The following sections describe the work done to refine the facility design and performance, the results of this refinement in terms of facility descriptions and costs, considerations of safety and site criteria, an assessment of the critical areas in developing the facility, and an analysis of the total facility acquisition schedule.

4.1 REFINEMENTS IN DESIGN AND PERFORMANCE

All work done in Phase III on this facility was concentrated on improvement of the design and specifications of the test legs and facility systems. The major goal was to refine the specifications so that the facility will meet its performance definition at a reasonable acquisition and operating cost. No performance compromises or redefinitions have been made.

The following tasks were performed in order to attain the goal of improved facility description and minimized costs:

(1) Structural and mechanical layout of both test legs was done by FluiDyne Engineering Corporation, using the Phase II facility sketches as a starting point. Their experience in facility design was useful in searching out and solving problem areas and in obtaining a detailed facility description. Test leg cost estimates were done using the Fluidyne drawings as a basis.

(2) A much more detailed analysis of total air requirements was performed. This was required because of the necessity to make sure that enough air storage volume and pressure were available, but without over-specifying these quantities. Specifically, studies were made of the ejector air flow requirements and minimum tunnel run times necessary to obtain the set goal of one full pitch or yaw polar per run. Flow establishment time was also included in the air storage requirements. These studies resulted in a considerable reduction of total storage volume for both test legs from the Phase II calculations.

(3) Consultation with personnel at AEDC and Allis-Chalmers revealed the possibility of a savings in acquisition cost if the facility were to be located at AEDC and if integration with existing equipment was employed. Specific considerations are: a) use of the AEDC-VKF compressor facility with addition of one machine to boost the available maximum pressure to 5000 psi (3450 N/cm^2); b) use of the AEDC-PWT model installation building; c) use of the AEDC 16T and 16S test section carts, with some modifications, and the cart transfer cars. The facility cost has been estimated with and without these integration possibilities included.

(4) A second part of the FluiDyne subcontract effort was the identification of safety hazards to personnel, test article, and facility. Procedures, safety interlocks, special subsystems, and control system rationale needed to operate the facility safely were described.

(5) The third part of the FluiDyne subcontract effort was the analysis of constructional problems and the development of an acquisition schedule for the test legs. The schedule is carried from development of basic specifications to facility shakedown and calibration. Similar analyses by MCAIR have been made and included on the acquisition schedule for the air storage system, the compressor plant, and the air heaters.

(6) In addition to the general site selection criteria developed in Section 2.6, operation of GD20 was analyzed to determine what specific site selection criteria were peculiar to that facility.

(7) The development risks, and acquisition and operational problems were evaluated for each major component, then compiled into an overall facility confidence level rating. The major problem areas associated with the major components and overall facility were identified.

(8) The facility was evaluated in terms of its ability to satisfy the performance goals specified originally in Phase I as necessary to accomplish the Research Objectives appropriate to GD20.

4.2 FACILITY DESCRIPTIONS AND COSTS

The size of the wind tunnel necessary to achieve a given Reynolds number was based on the following factors:

(a) wing bending strength in the spanwise direction

(b) fuselage bending strength in the chordwise direction

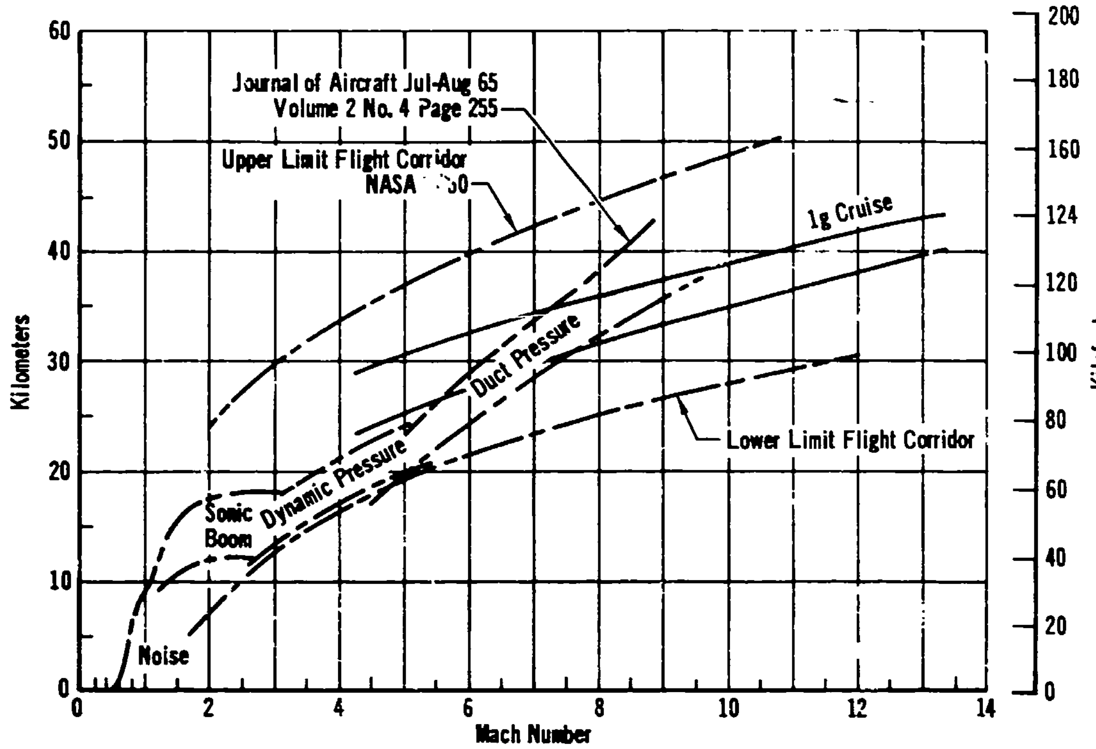
(c) balance load carrying capacity

(d) starting loads for blowdown type wind tunnels

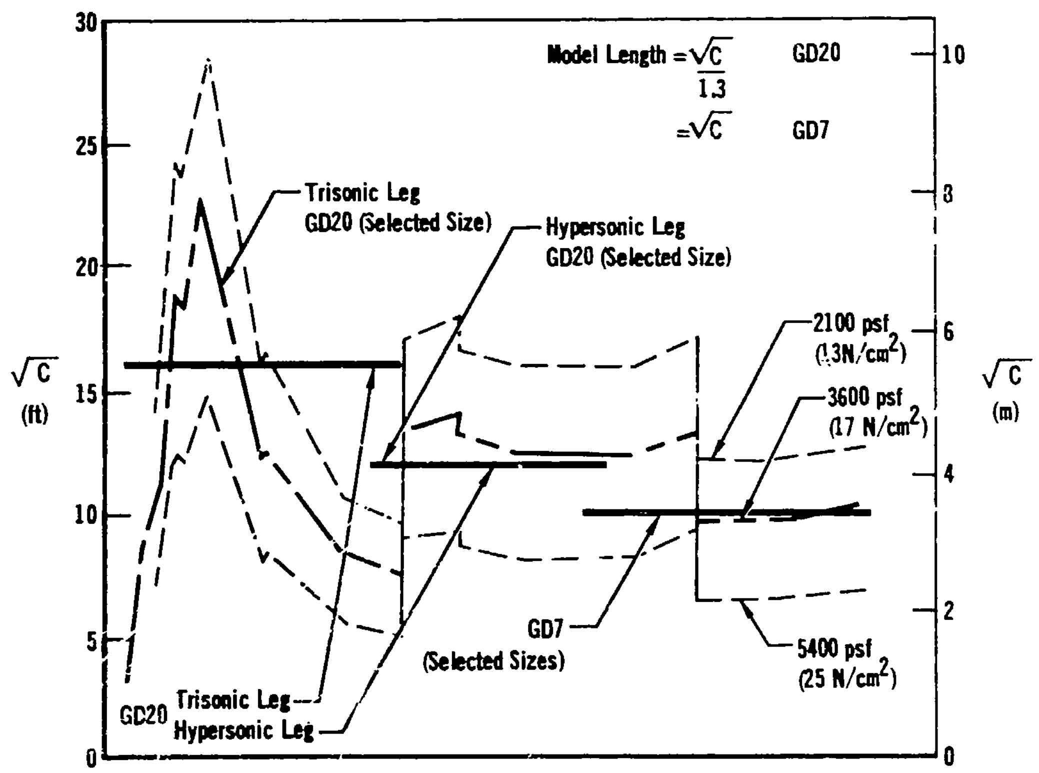
(e) balance natural frequency compared to run time.

These criteria were evaluated for present day aircraft as well as the nine HYFAC potential operational hypersonic aircraft. The evaluation showed that balance limitations governed the level of dynamic pressure which a model balance combination could sustain for the HYFAC type configurations. A facility sized to attain a maximum Reynolds number for hypersonic aircraft was also suitably sized to obtain maximum Reynolds numbers for subsonic and supersonic aircraft as well, thus providing an additional dimension of facility applicability. The reference trajectory used to determine the maximum Reynolds number conditions, and the tunnel sizes is shown in Figure 4-1. The range of dynamic pressures shown represents the range encountered in examining the nine potential operational hypersonic aircraft. The sizes shown have remained unchanged since Phase I. It may be argued that perhaps

FIGURE 4-1
FLIGHT ENVELOPE, POTENTIAL OPERATIONAL HYPERSONIC AIRCRAFT



Minimum Facility Size Requirements



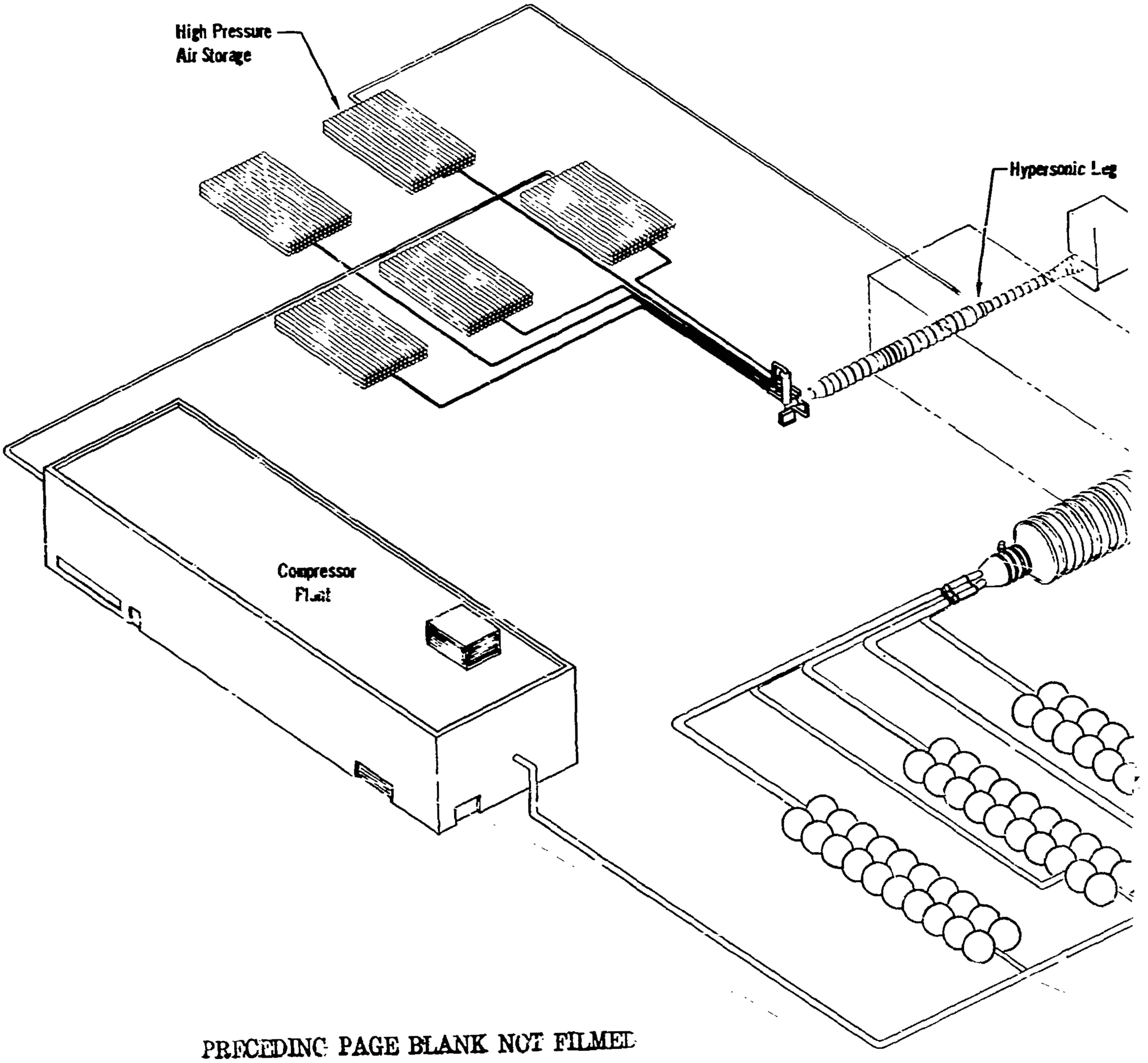
a larger trisonic leg for GD20 could be justified, however, it appeared that the advantages of providing interchangeable test sections with AEDC 16S and 16T facilities overshadowed the benefits derived from a slightly larger test section size. The definition for required test section size developed in Phase I was the basis for all of the facility component definitions presented in Sections 4 and 5.

The Polysonic Gasdynamic facility is subdivided into a number of elements to facilitate the discussion of component description, cost, and development assessment. The overall general arrangement of the facility complex is presented in Figure 4-2, and of the test legs in Figure 4-3. The order of discussion is the Trisonic Test Leg (Figure 4-4), Hypersonic Test Leg (Figure 4-5), Storage Volume and Blowdown Lines, Compressor Plant, and Heaters. Because of the complexity of the test legs, the description of each test leg is divided into Pressure Shells, Control Valves, Flexible Nozzle Assembly, Test Section, Adjustable Diffuser and Supersonic Ejectors, and Muffler.

4.2.1 TRISONIC TEST LEG - This test leg is basically a very large version of existing blowdown wind tunnels, with some special design features provided to enhance its usefulness and flow quality. Details of the test leg are shown in Figure 4-4 and 4-5, while Figure 4-3 presents an isometric view of the test leg and Figure 4-2 shows the entire facility with its support systems.

The basic concept of the test leg is that a flexible plate nozzle is provided, which can be set, by means of electric screw jacks, to a predetermined contour which will provide a Mach number range of 1.0 to 5.0. Air, controlled to a desired set-point stagnation pressure by throttling valves, enters the stilling chamber and is expanded to the nozzle Mach number. A variable throat diffuser is used to convert the kinetic energy of the test section flow to pressure. The diffuser throat opening is set to optimize flow starting and maximize run time. The flow exits to atmosphere through muffler designed to silence the flow and direct it upwards. For subsonic or low transonic operation, the nozzle is set at its sonic contour and is run at a subcritical pressure ratio, that is, sonic conditions are not reached in its throat. This is done by closing the diffuser throat to a position such that sonic conditions exist at the diffuser throat. An alternate way of doing this, not shown, would be to incorporate simple choking flaps in the diffuser sidewall. Doing this would minimize the required diffuser plate travel, but could induce adverse pressure gradients in the test section. Adjustment of the diffuser or choking flaps to different settings provides the necessary subsonic flow in the test section. For transonic operation, Mach control is provided by a combination of diffuser setting and provision of a controlled amount of suction through the porous walls of the test section. Plenum suction is provided by the transonic ejectors and controlled by throttle valves on each ejector secondary flow passage.

FIGURE 4-2
PLANT GENERAL ARRANGEMENT - GD20



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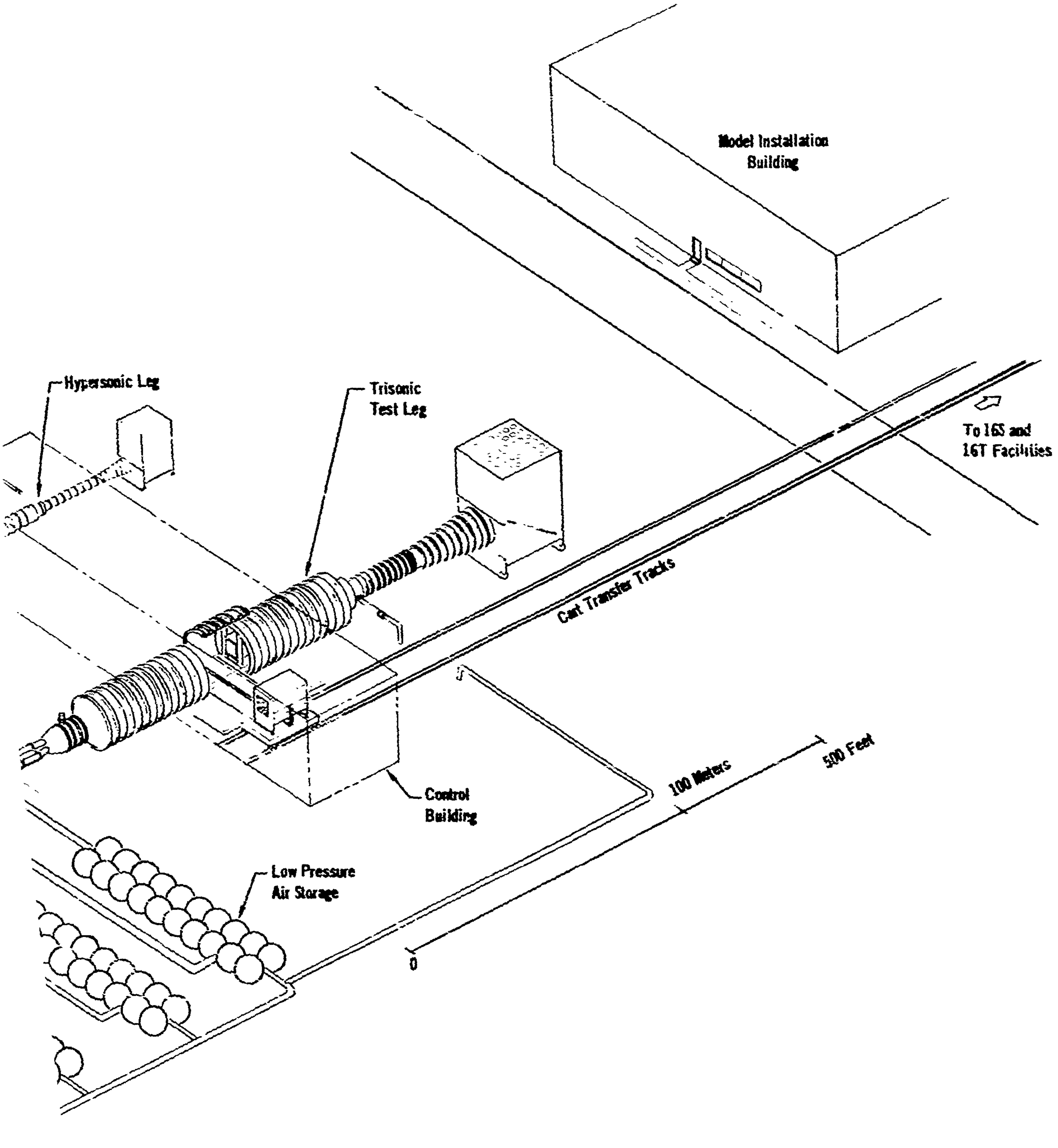

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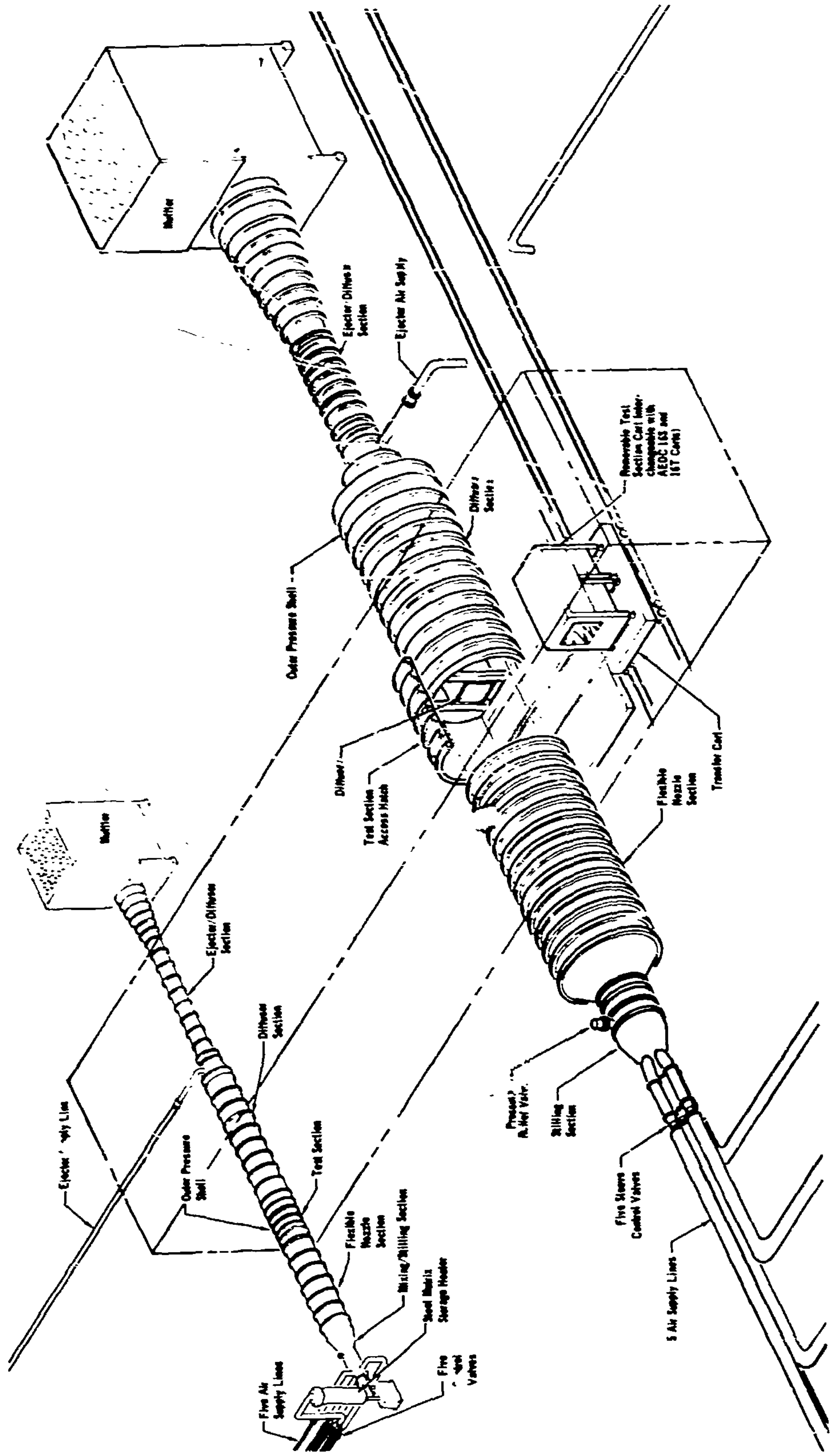

FIGURE 4–3
TEST LEG GENERAL ARRANGEMENT – GD20

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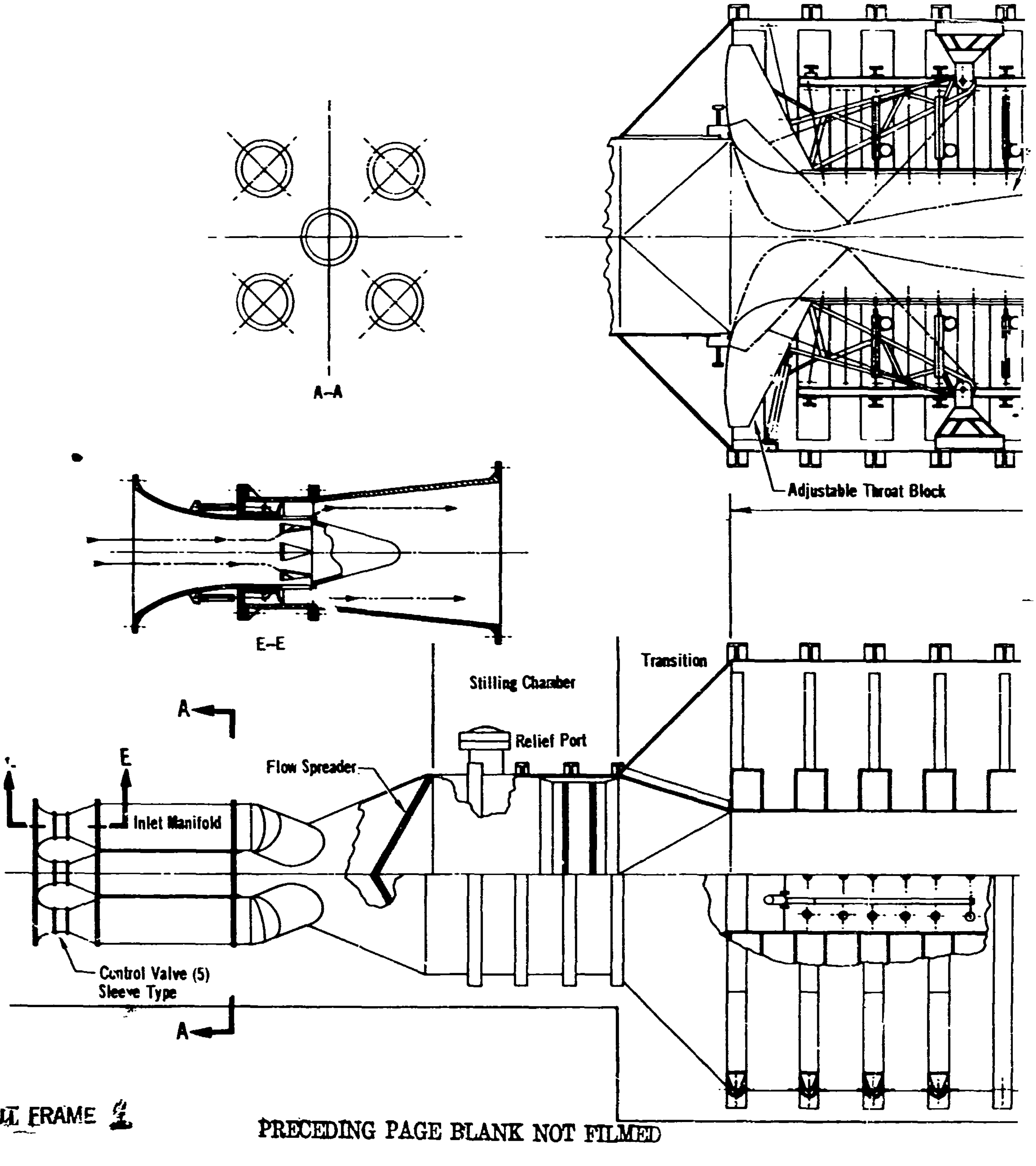
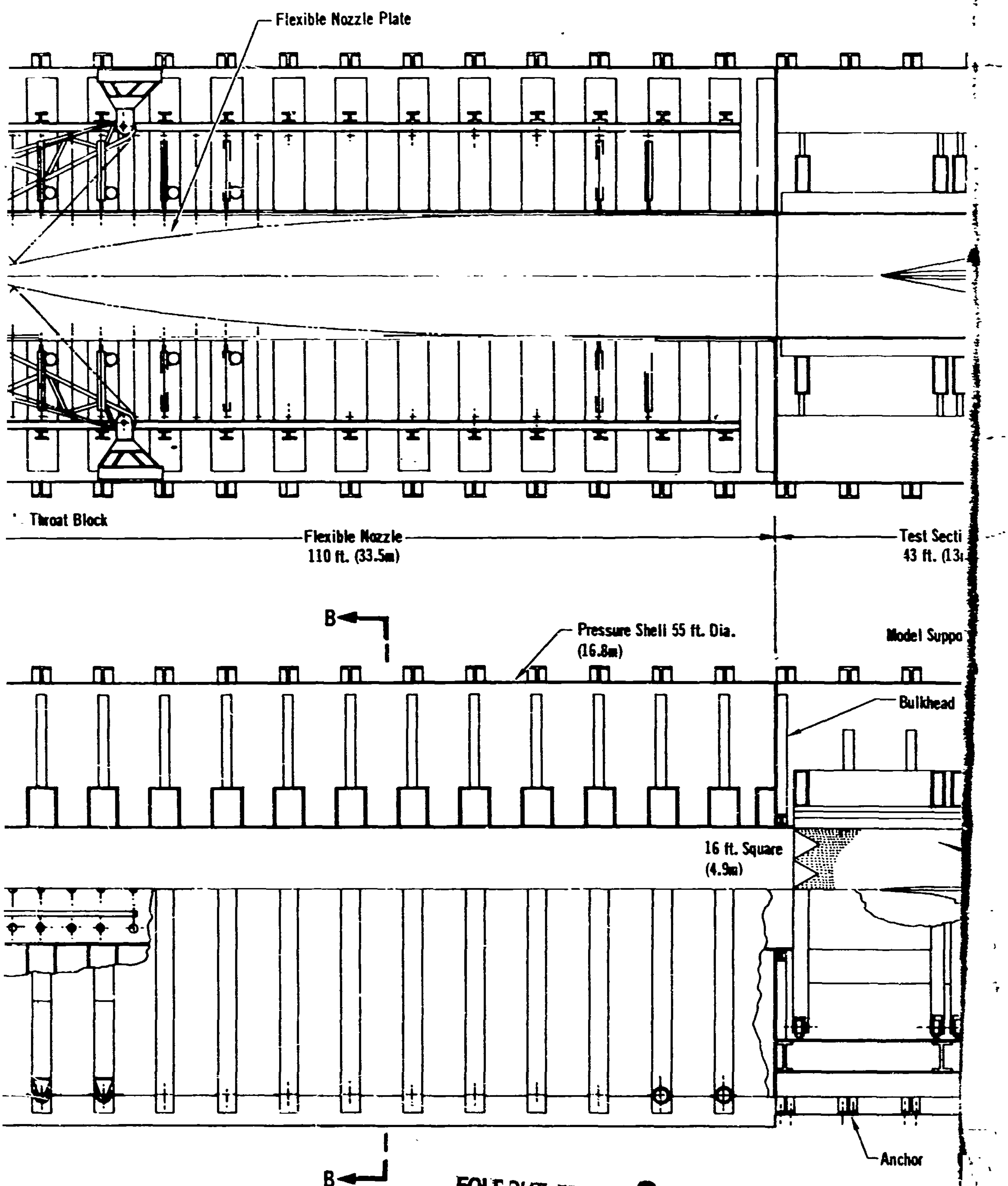
FIGURE 4-4
GD20 GAS DYNAMICS FACILITY - TRISONIC TEST LEG





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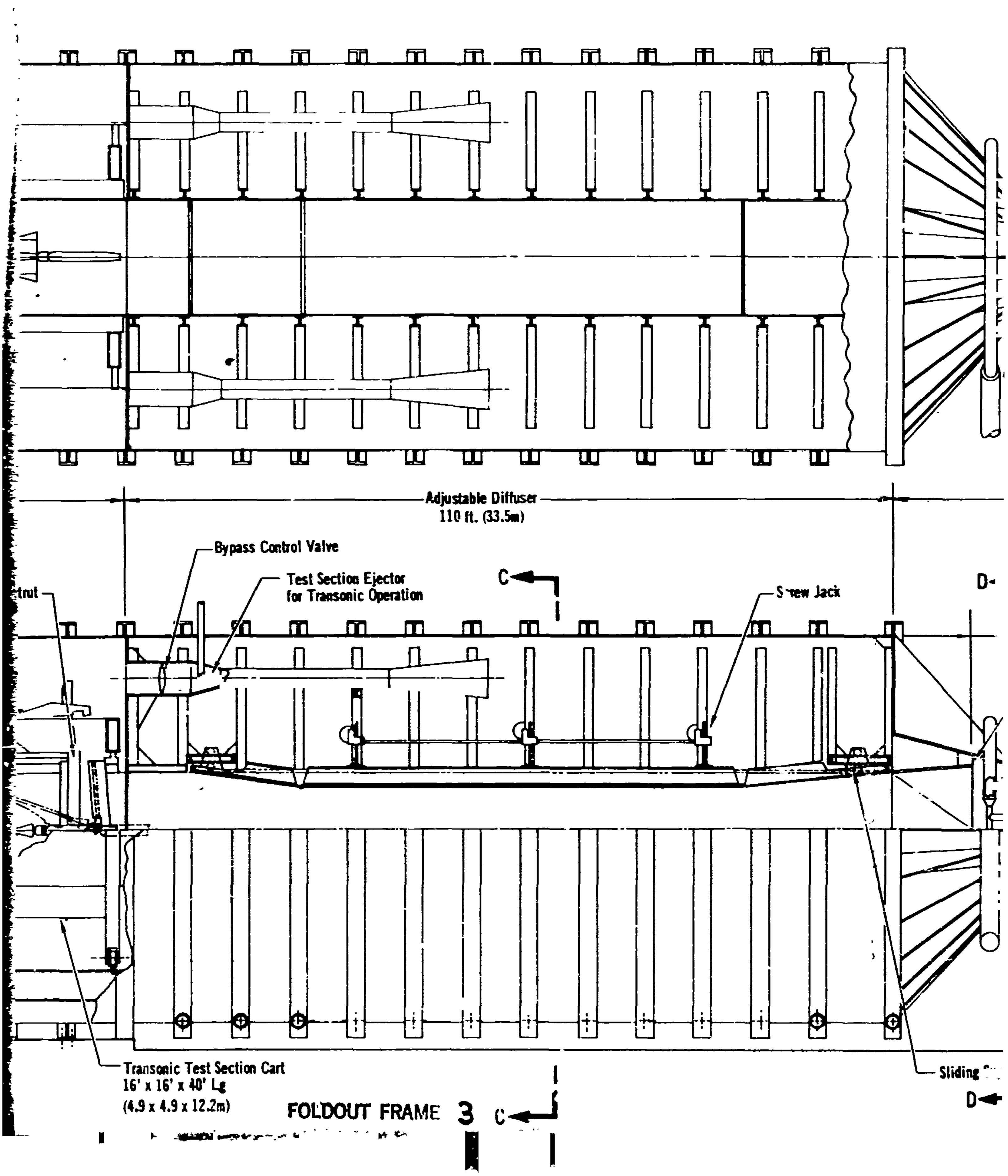

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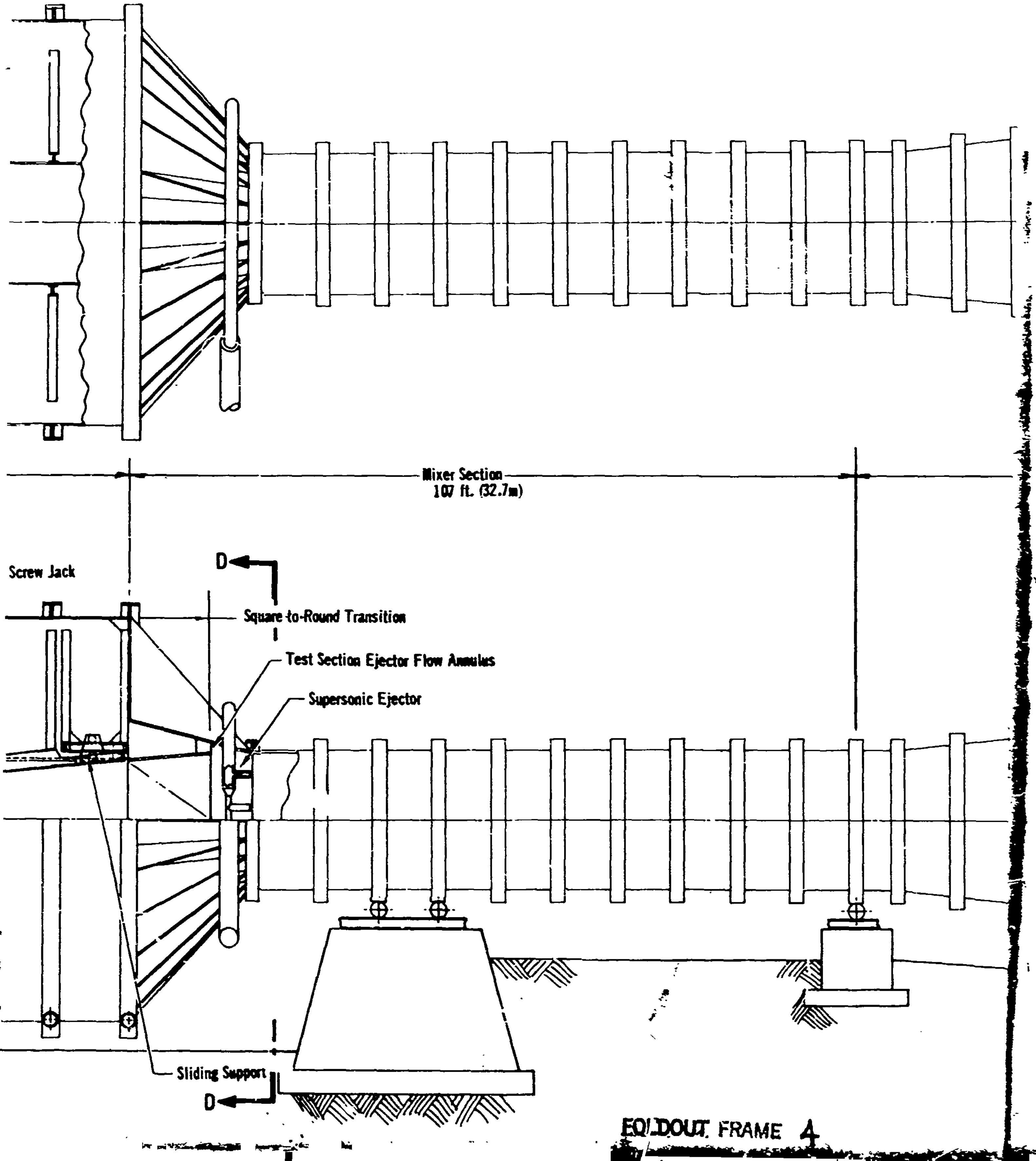

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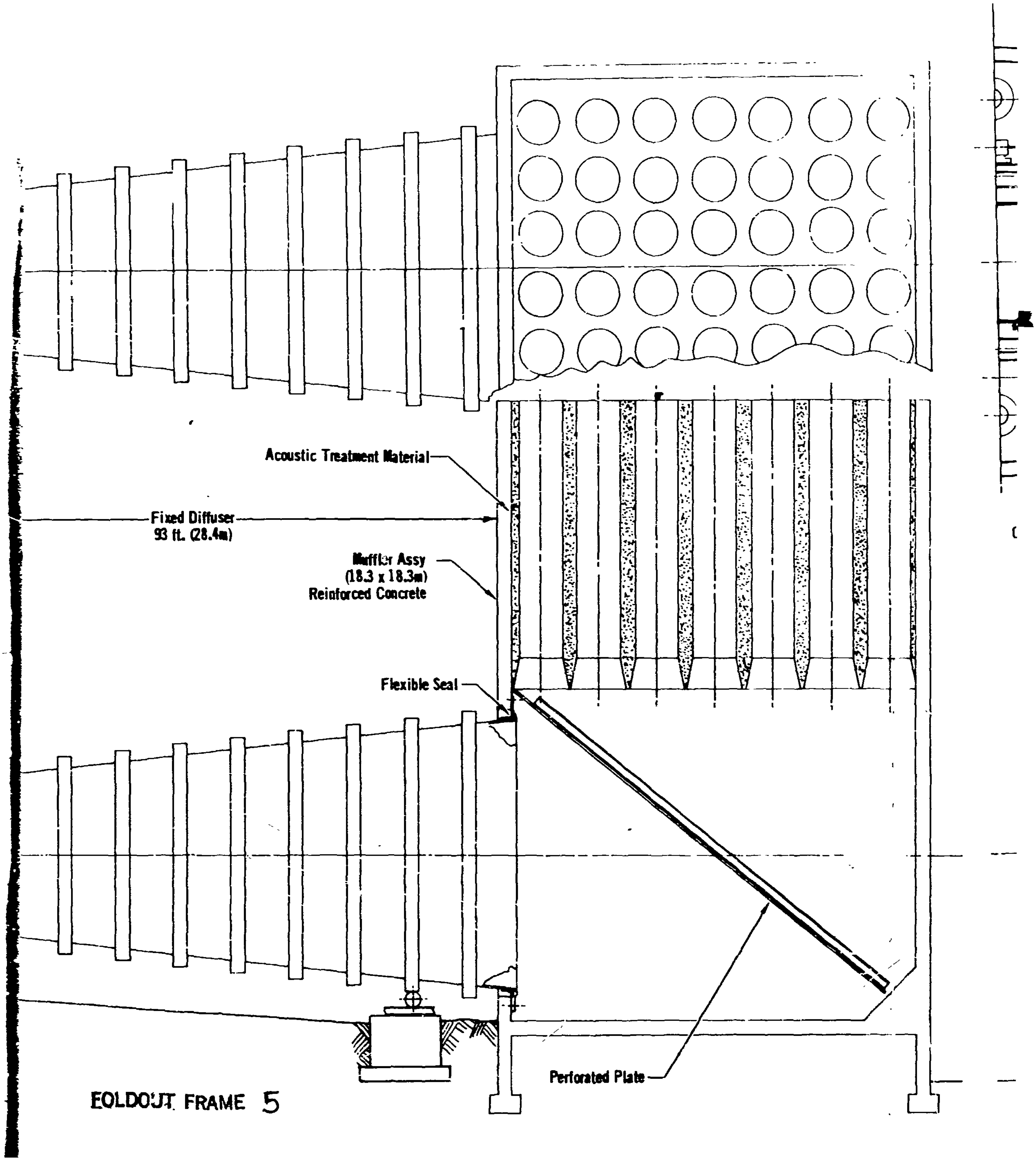

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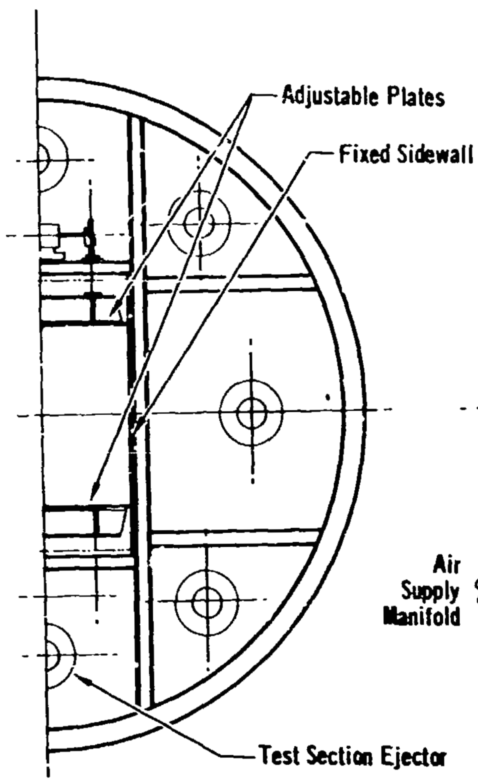
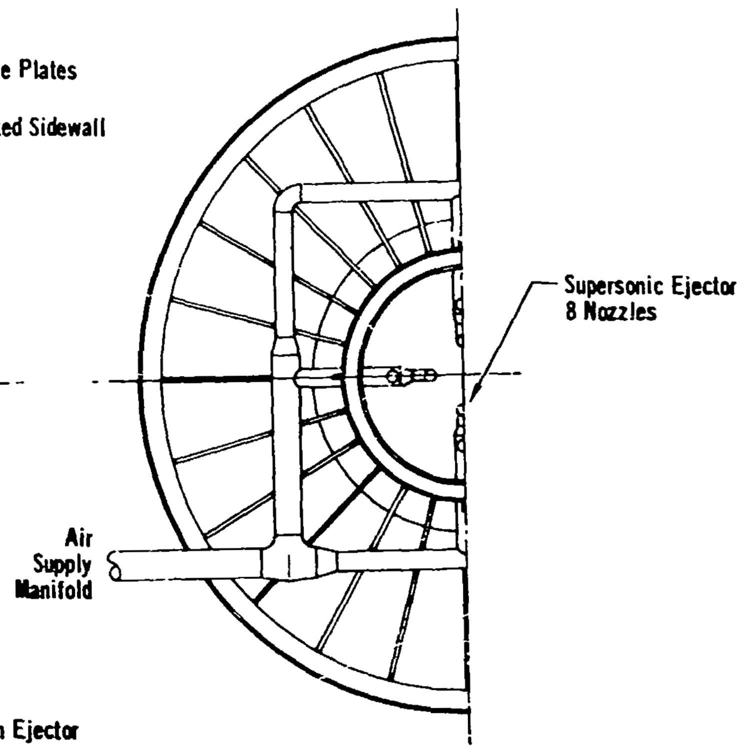
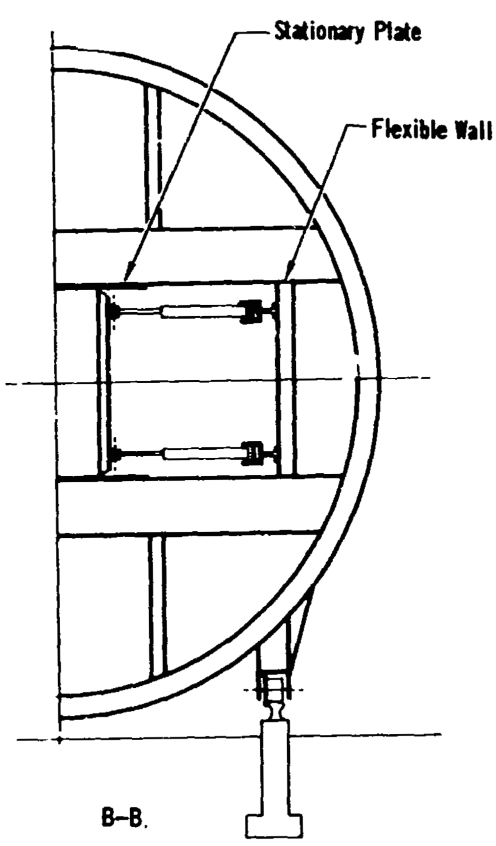
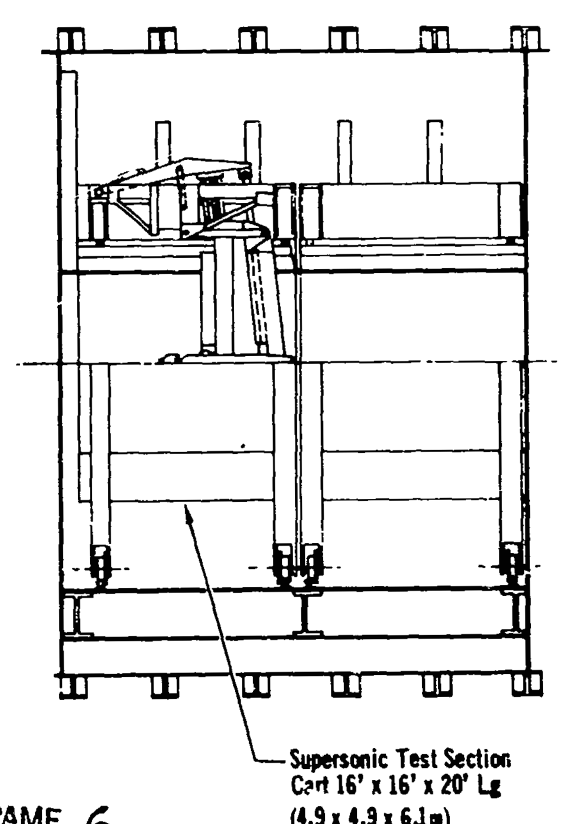


C–C



D–D

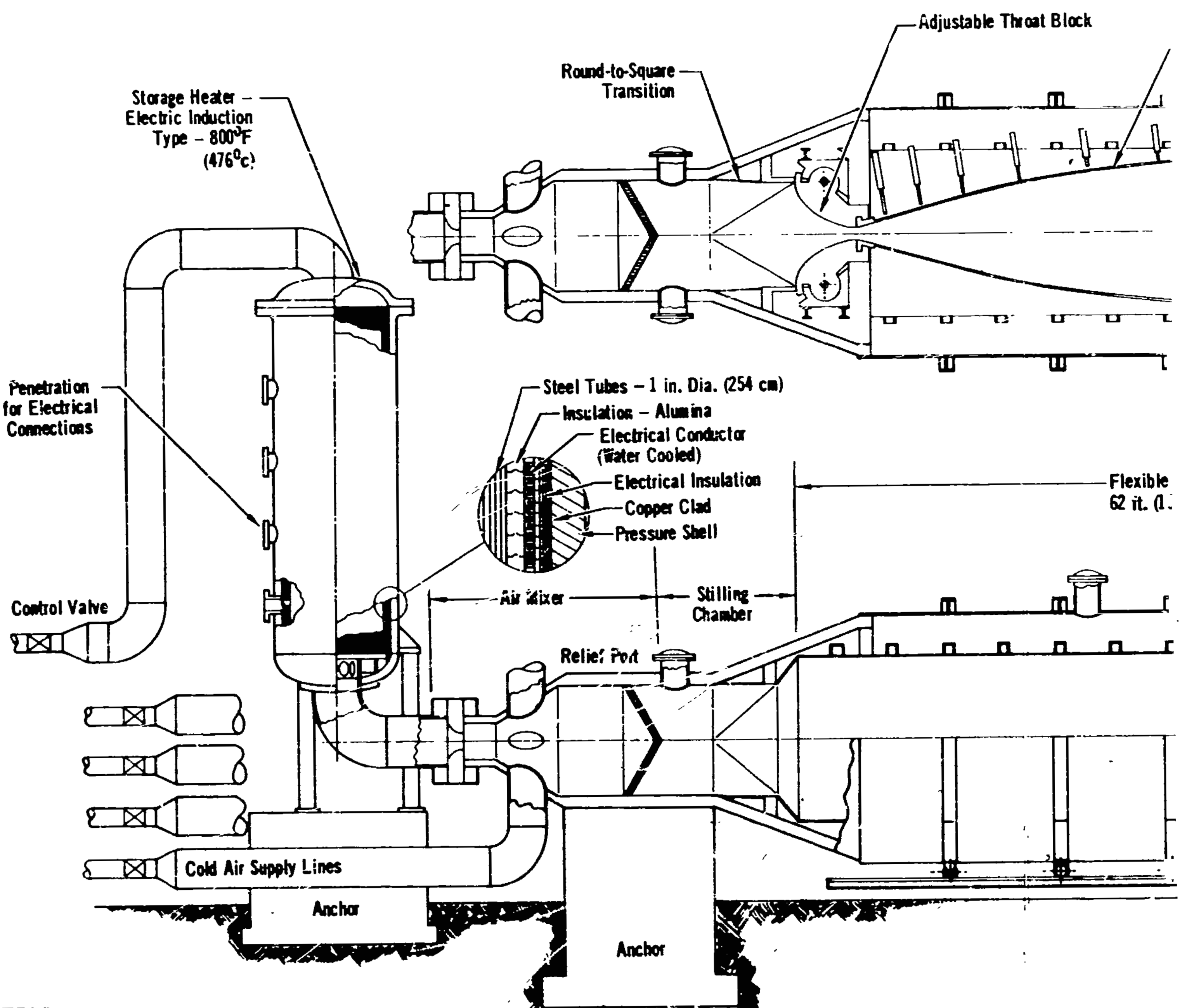




B–B.

FOLDOUT FRAME 6

FIGURE 4-5
GD20 GAS DYNAMICS FACILITY - HYPERSONIC TEST LEG



FOLDOUT FRAME 1

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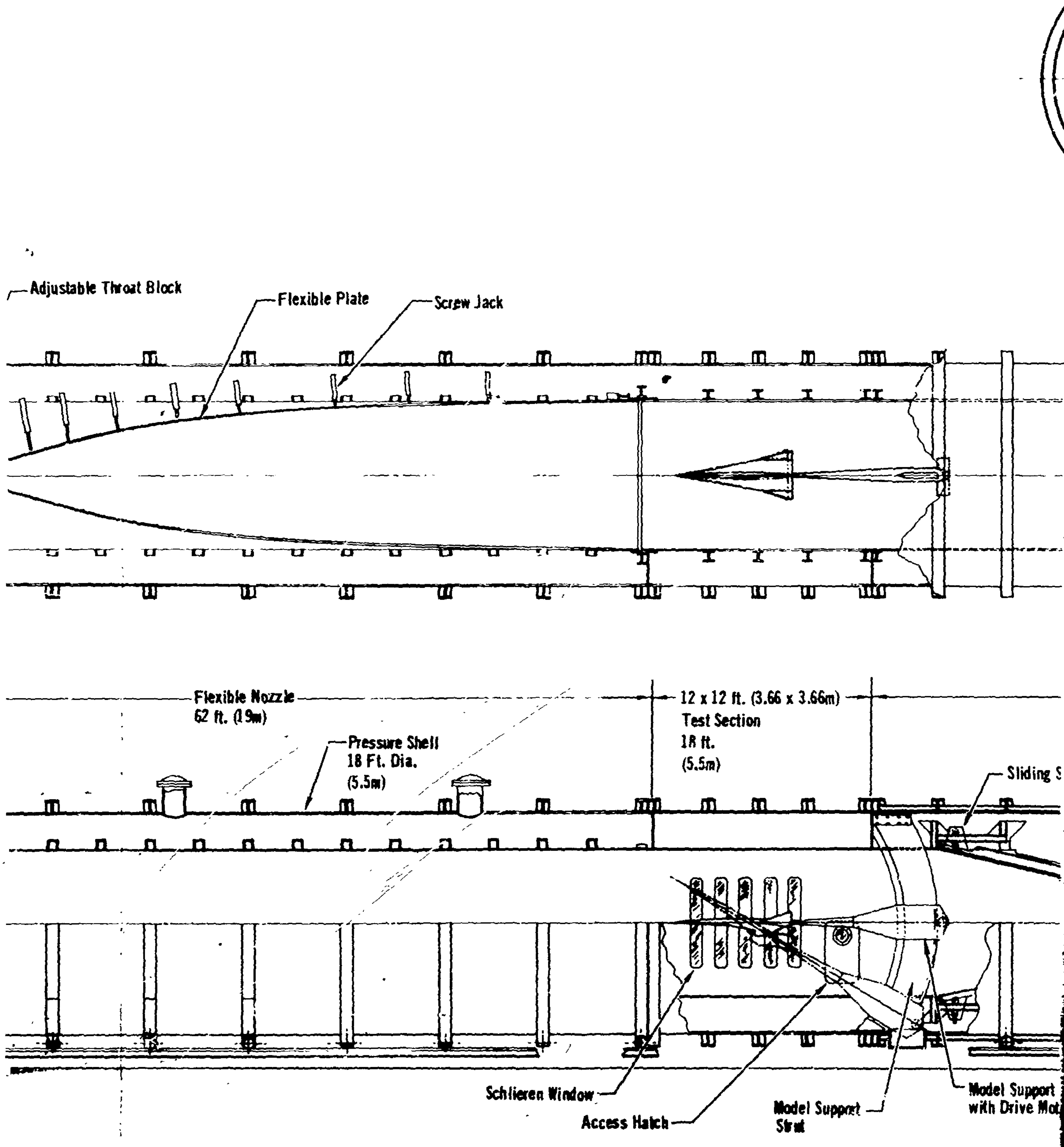
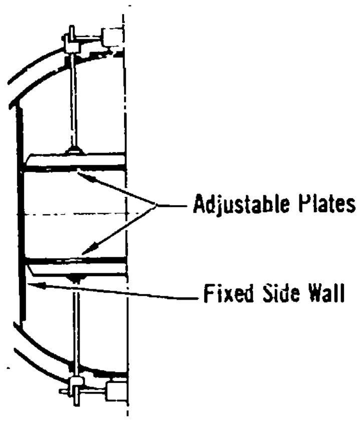
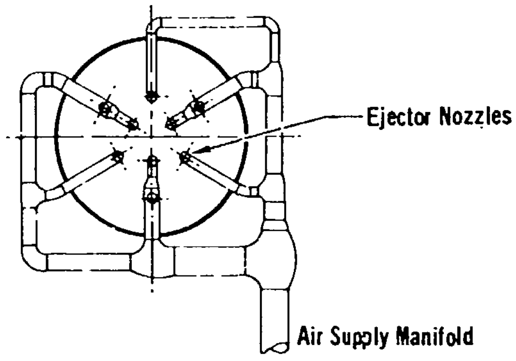


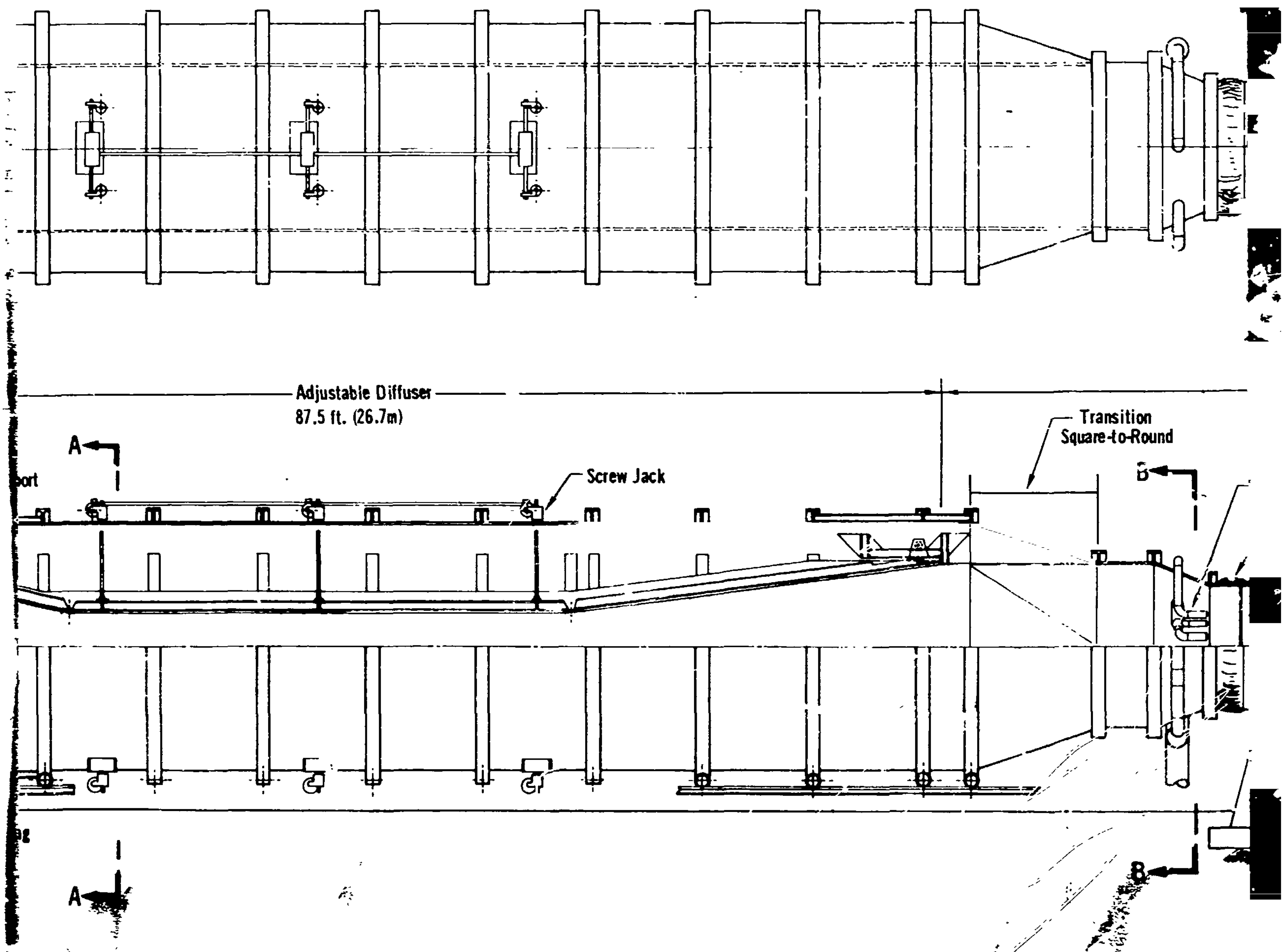
FOLDOUT FRAME 2



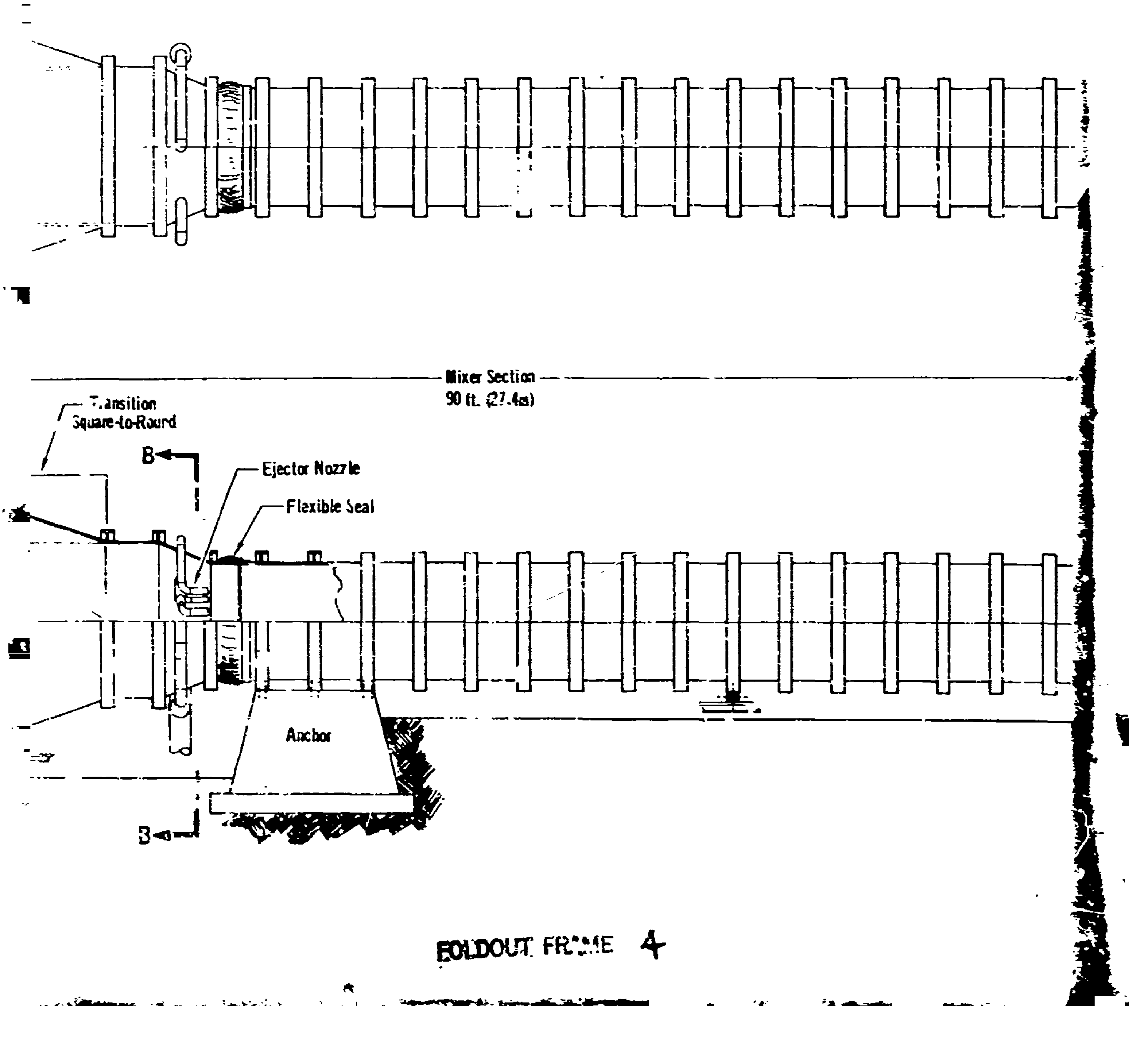
A–A



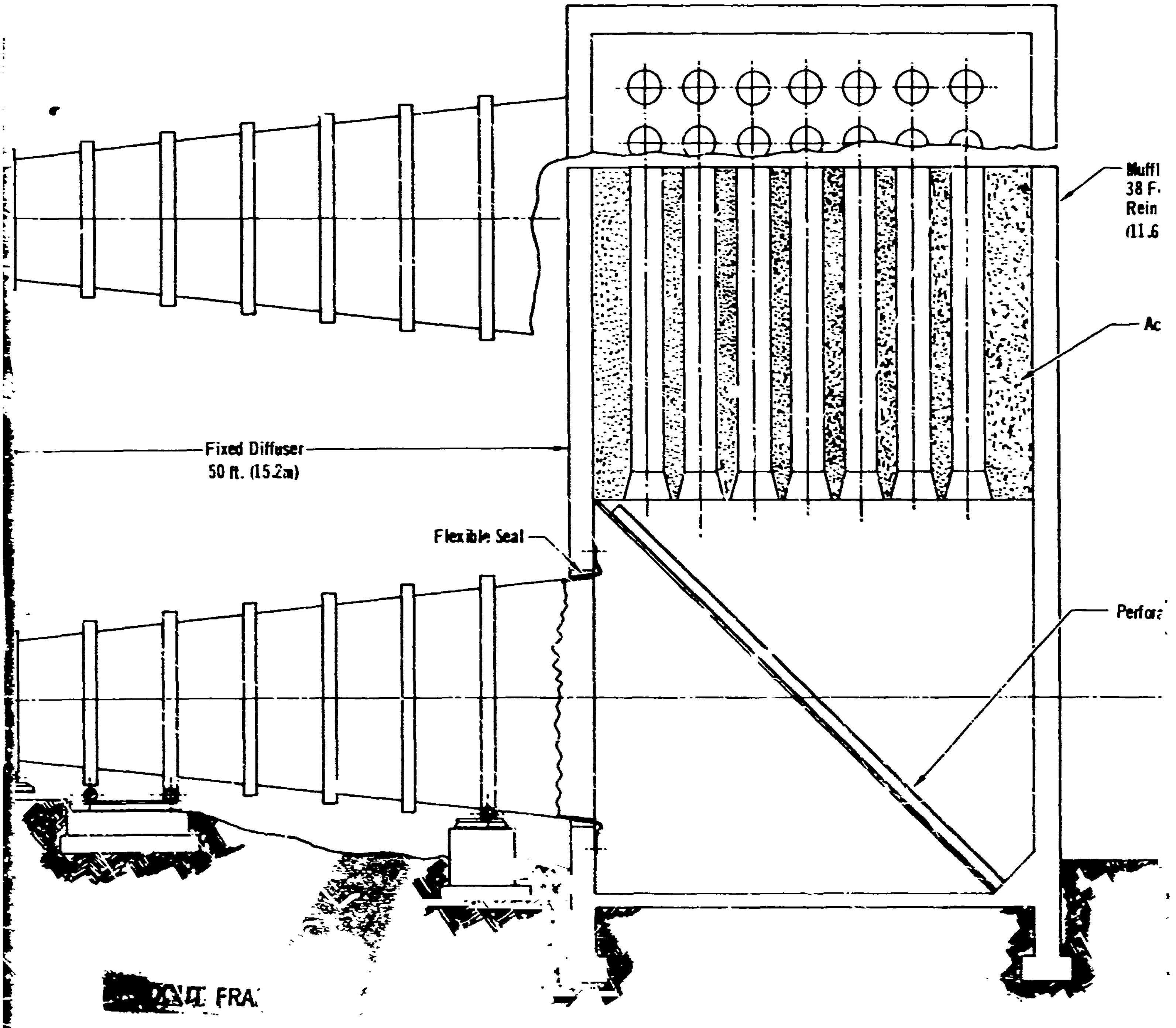
B–B



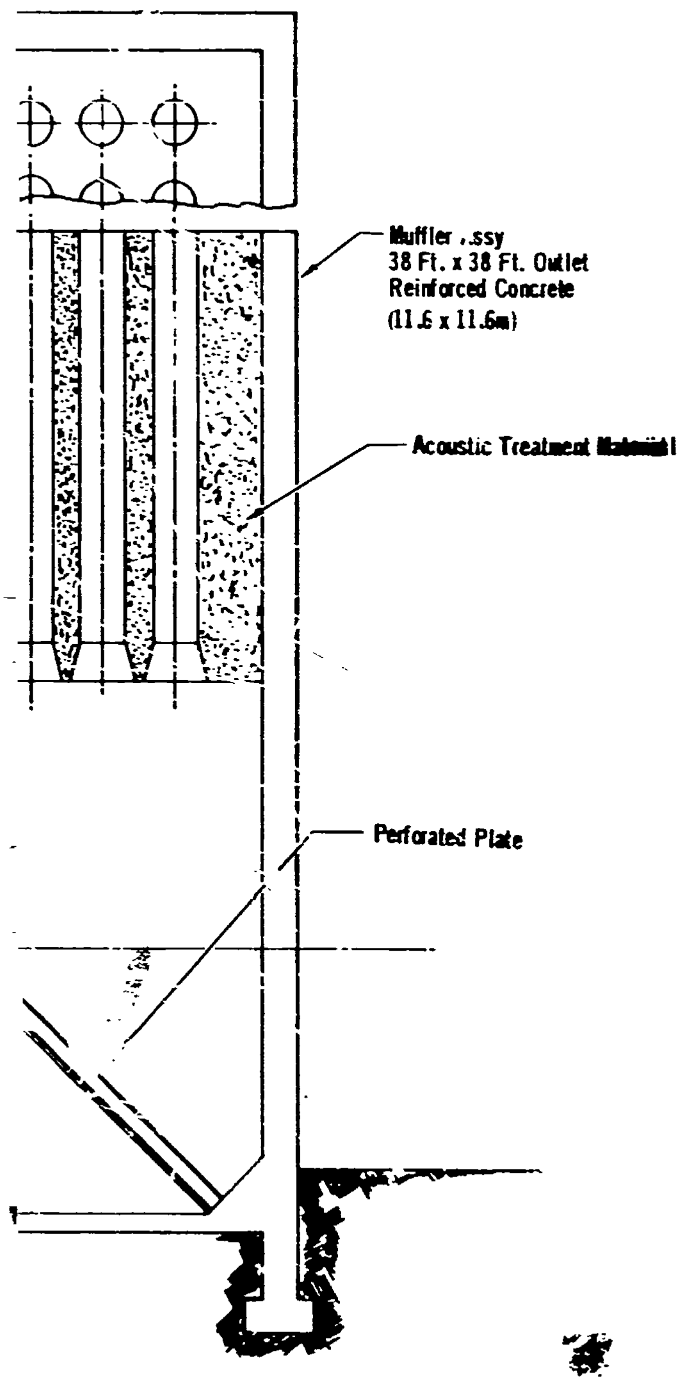
FOLDOUT FRAME 3



FOLDOUT FRAME 4



FOLDOUT FRAME 5



FOLDOUT FRAME 6

A typical run starts by establishment of ejector flow. As mentioned, the transonic ejectors are used primarily for Mach number control. The supersonic ejectors, however, are used to pump the tunnel down to about 1/2 atmosphere in order to increase the overall tunnel starting pressure level. This permits the establishment of supersonic test section flow at a minimum stagnation pressure, and minimizes the time during which the starting shock wave pattern is passing over the model. Both lower stagnation pressure and minimum starting transient time are necessary to minimize the total starting loads on the model and balance, which can be as high as 5 times the normal running loads. Once steady flow is established at a constant set-point stagnation pressure, the model starts its pitch program and data is taken. For transonic operation, the plenum bypass control valves are automatically modulated, holding plenum pressure, and thus Mach number, constant throughout the run. This must be done because the model, as it pitches, causes a wide variation in test section blockage and thus plenum pressure. Upon completion of the model pitch schedule, the model is returned to zero angle-of-attack, the main control valves are closed and, once the flow breakdown shocks pass by the model, the ejector control valves are closed.

Safe operation of the trisonic test leg will require that specific operation procedures and permissive circuits be developed to assure protection of personnel and equipment. The primary personnel safety concerns and preventative measures are summarized in Section 2.5. This facility does not present any unusual safety problems in regards to personnel.

Discussion of the design features of the test leg components, problem areas, safety considerations, and construction techniques follows.

(a) Pressure Shell - The pressure shell is comprised of the inlet manifold, stilling chamber, transition section, and the entire outer shell to the muffler. Construction is standard practice, the shape being circular, with exterior stiffening rings and interior bulkheads and framework supporting the flexible nozzle, test section, and diffuser. Except for the stilling chamber and transition section, the shell is constructed to withstand an internal pressure of ± 15 psig (± 10.3 N/cm^2). The stilling chamber and transition section must withstand up to 400 psig (270 N/cm^2), but represent no difficult design problems. Access should be provided in this area to allow inspection and maintenance of the flow straightening hardware and the throat block section of the adjustable nozzle. Pressure relief hardware, adequately sized, will be necessary in this section. The access doors should be interlocked and an emergency stop switch located inside the stilling chamber. The entire tunnel structure is anchored at the test section location and is uniformly supported on rollers the length of the 55 foot (16.8 m) diameter section. A flexible seal at the muffler end allows for growth due to thermal expansion.

This large vessel must be field fabricated and will present fabrication and erection challenges previously covered in Section 2.5. The nozzle and diffuser sections of this shell will require pressure relief equipment to prevent damage in the event of seal failure.

Although very large, similar structures have been constructed and the pressure shell has a confidence level of 5.

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(b) Control Valves - The tunnel airflow is handled from storage to the nozzle plenum through five 70-inch (1.78 m) pipe lines. Stagnation pressure control is achieved utilizing five sleeve valves. Multiple control valves (and supply lines) were selected because of the wide range of mass flow that must be controlled. When any valve is trying to control flow in a nearly closed position, it will be subject to flow/servo system dynamics, or "hunting", with resultant poor control of the downstream pressure. In addition, in the nearly closed position, there is separation of the flow and high turbulence. This is especially undesirable in this design, since stable and uniform filling of the stagnation chamber is necessary for uniform test section flow properties. Severely throttled flow is also very noisy, another undesirable feature, since such noise will be present in the test section freestream. In addition to the aerodynamic and control problems posed by nearly closed operation, there is greatly accelerated wear of the valve trim to consider.

The selection of multiple control valves ensures that even at weight flows one-tenth of the maximum, the functioning control valve will be operating in mid-range, since at low flow rates only the minimum number of valves will be used, the others being shut tight.

Sleeve valves were selected in order to ensure symmetrical flow at all valve positions, thus aiding stilling chamber flow stability and uniformity. It is also desirable to use a valve such as shown, where the actuation force is independent of pressure difference across the valve.

Sleeve valves of the type considered have performed satisfactorily in other similar installations. However, the valves envisioned here are larger and the pressure rating is higher. A completely tight shutoff may be extremely difficult to accomplish, and is not required, since shutoff valves are contemplated near the air storage area. The valve manifold arrangement should be such to allow ease of maintenance and allow each valve assembly to be removed and replaced without interfering with the remaining four. To prevent long facility downtime, consideration should be given to maintaining a valve inventory.

The sleeve valves will require an automatic control system. For both transonic and supersonic operation the valves will control to a fixed stagnation pressure set-point. An automatic sequence will open one valve as the pressurization process begins. As the valve reaches 85% open, another valve will open, and so on until full set-point pressure is reached. As the storage tank pressure decreases, the valves continually open, keeping the downstream pressure constant. At the conclusion of a run, any number of valves from one to five may be open. Upon completion of the model data program, all valves are rapidly closed.

As regards safety, consideration must be given the pressure control valving and stored air arrangement in that the sleeve valves may not seal completely. It is anticipated that a shutoff valve near the air storage will adequately isolate the test leg from the air storage. Normally, two shutoff valves are desirable between personnel working areas, such as the test section, and the air supply. The hydraulic actuation system and electric control circuit must be "fail-safe", forcing the valves to close upon loss of hydraulic pressure or electric power. A two-key interlock control system must be provided so that removal of the key required to gain access to the tunnel circuit at any point immobilizes operation of the valve control circuit key.

These valves, although of a type similarly employed in existing facilities, must be considered to require a design study and prototype development because of their size and pressure rating, and are assigned a confidence level of 3.

(c) Flexible Nozzle Assembly - An adjustable nozzle with a 16-foot (4.9 m) high by 119-foot (36 m) long flow surface will provide the most complex design problem. 16-foot high adjustable nozzles have been built and are currently in operation. However, the operating pressure levels are lower and individual Mach ranges are smaller. As envisioned in this study, the adjustable nozzle is actually two components; a throat block and flexible plate. Each throat block must travel to within approximately 3.5 inches (9 cm) of the centerline (total travel approximately 7.7 feet (2.3 m)), seal at the upstream face against stagnation pressure, and take out the pressure load at the pivot point of the block. The flexible plate is mounted to the throat block and both are preset to the desired Mach number configuration utilizing screw jacks. This plate must necessarily be thin and flat in addition to providing jacking points on the back side which uniformly distribute the load. If welding is contemplated in the fabrication of this large flexible nozzle plate, the development of special techniques may be required. Sliding seals along the length of the adjustable nozzle may require some development. If a seal is not achieved, recirculation will occur and may disturb the nozzle flow distribution.

Specific procedures for nozzle adjustment will be required such that possible damage to the block, plate, or jacks is minimized. Once the nozzle has been reset and checked, this information should be programmed into the interlock system as being ready for wind tunnel operation. Access must be provided in the 55-foot (16.8 m) diameter pressure shell for inspection, maintenance and repair of the adjustable nozzle, seals, and screw jacks. This access must be interlocked and an emergency stop switch located on the pressure shell behind the adjustable nozzles. Pressure sensors should be placed at various locations in the cavity behind the adjustable nozzle to indicate unusual pressure buildup or the existence of recirculation due to seal leakage. The sensors would be integrated into the interlock system. The flexible nozzle assembly, because of its pressure requirements, size, and large Mach range is assigned a confidence level of 3.

(d) Test Section - The test section consists of a cylindrical pressure shell with a side opening hatch and a removable cart model support system. Structural bulkheads at the nozzle exit and diffuser entrance isolate and support this section of the pressure shell. A cart system, which is moved on rails between a model assembly area and the test section, is contemplated. The cart, which contains the test section flow surfaces, model support, and pitch mechanism, is similar to that currently employed at AEDC. Two carts are needed, one with porous walls, for transonic operation, and the other with solid walls, for supersonic operation. Other than being large, there [illegible] apparent design or fabrication problems contemplated. The mating surf[illegible] cart and the adjustable nozzle and adjustable diffuser will requi[illegible] at[illegible]tion to assure alignment. Test cart service connections will [illegible] the cart is locked in the proper position. These service lines [illegible] ar[illegible] support drive power (electric or hydraulic), water, air, [illegible] frequent maintenance and inspection. The cart service lines [illegible] with sensors which indicate loss of electric power, balance over[illegible] down before damage occurs to the model or support system. [illegible] procedure will be to quickly bring the model to zero angle [illegible] shut the control valves.

For transonic operation, test section suction is provided using eight air ejectors operating within the pressure shell housing the adjustable diffuser. The ejectors will operate at a constant stagnation pressure. This pressure will be maintained by a single automatic control valve operating in the supply line upstream of a manifold to the eight ejectors. Control of the test section suction is achieved by utilizing butterfly valves at the inlet to each ejector. The eight ejectors and automatically controlled butterfly valves will be operated simultaneously to achieve uniform test section suction. The valves will be controlled individually to hold constant test section Mach number by a servo system using the local plenum pressure as input. It is also possible to program different sidewall suction rates on each wall to allow fine Mach control for models with very strong downwash. Ejector and plenum bypass flow re-enters the main stream aft of the adjustable diffuser.

The concept of the removable test carts is critical to the entire facility concept. Model installation time in such large facilities can range from two or three days for simple tests to several weeks for sophisticated installations. With removable carts, all model installation work is performed in a remote model installation building. Thus, a very high utilization of the test section is possible, and the customer gets a maximum number of runs for a given test budget. If the facility is located at AEDC, the transonic and supersonic carts could be installed in the 16T and 16S propulsion wind tunnels as well as GD20. This feature provides flexibility if a test on a given model is to be run both in GD20 and one of the other tunnels. Likewise, the existing carts at AEDC can be used in GD20 with some modification to withstand the maximum wall static pressure of 30 psia (20.6 N/cm^2). The estimated cost of the test leg in the integrated version assumes that no new carts will be built and that the existing AEDC carts will be used. Also, no cost for a model installation building is included in the integrated version costs, the use of the existing building being presumed.

Since the size and performance of all the test section components is currently available, a confidence level of 5 is assigned.

(e) Adjustable Diffuser and Supersonic Ejectors - The adjustable diffuser is used, as mentioned previously, both as a sonic choke for subsonic testing and as a pressure recovery device during supersonic testing to maximize run time.

The adjustable diffuser features sliding supports at the upstream and downstream end which allows the screw jacks to be operated with straight vertical motion. A sliding seal in the adjustable diffuser will be required which seals against the sidewall. The screw jacks are motor driven to a predetermined closing depending upon the test conditions and this preset closing program should be incorporated as a prerun configuration manual interlock.

Consideration must be given to the fact that, as presently shown, the test cabin ejectors exhaust into the shell behind the adjustable diffuser. This may impose an added design problem for the screw jacks and seals. As with the adjustable nozzle section, access must be provided to allow inspection, maintenance, and replacement of jack and seal components. The access hatch and pressure shell should be interlocked to prevent operation with the hatch open or personnel inside.

Although the ceiling and floor of the diffuser are shown as the moving components, consideration should be given to use of the sidewalls instead. Actuator force would be decreased, since only friction and inertia forces would be opposing sidewall motion.

A point to be resolved is whether the actuator system need have the capability to move the diffuser walls during a blowdown. In this mode of operation, the tunnel would start with the diffuser throat adjusted to the size required to pass the normal shock system. Once the flow is started, the diffuser would close down to a minimum running position. This permits running at lower stagnation pressures (and Reynolds numbers), or for longer times than does a diffuser set only for the starting conditions. Balanced against these advantages is the fact that the diffuser actuation system has to operate very quickly and accurately to do any good, and would be relatively expensive. It might be noted that many tunnels which are equipped with this capability never use it, their run times being adequate for the testing at hand.

The supersonic ejectors are straightforward air-to-air ejectors, and are used to lower the test leg starting pressure and minimize model starting loads as previously described. Use of the ejectors is required to run the lower Reynolds number boundary shown in the performance plot. The ejector system consists of four primary nozzles, operating at a fixed stagnation pressure, and a long, constant diameter mixing section. The mixing section is required to develop maximum efficiency over a large range of tunnel flow conditions. The supersonic flow ejectors are mounted just downstream from the square to round transition section and are operated utilizing the same storage air as the primary flow. A single automatically controlled valve upstream of the ejector manifold regulates the ejector flow pressure. This control valve operation is interlocked to prevent inadvertent opening.

The confidence level of the adjustable diffuser and ejector is 4.

(f) Muffler - Downstream from the ejector mixing section and subsonic diffuser the flow enters a muffler designed to attenuate low and high frequency noise levels. The muffler assembly has a perforated plate at the inlet for low frequency attenuation and high frequency noise is handled in the tube type exhaust stacks (see Appendix A). The structure is reinforced concrete. Access to the muffler for inspection and maintenance should be provided and an emergency shutdown switch and access door interlock incorporated into the system. Because of its size, the muffler is assigned a confidence level of 4.

Cost of the total trisonic test leg including the blowdown valves is estimated at $27,500,000, when constructed independently of any existing facility, and $21,100,000 when integrated at AEDC. A breakdown of this cost estimate is given in tabular form in Section 4.2.6.

The confidence level of this test leg is 4.1, based on the weighted average of the component confidence levels.

4.2.2 HYPERSONIC TEST LEG - This test leg is a straightforward blowdown wind tunnel, exhausting to atmosphere. Heat addition is used to avoid air liquefaction at the higher Mach numbers. Details of the test leg are shown in Figure 4-5, while Figure 4-3 shows an isometric view of the test leg and Figure 4-2 shows the entire facility with its support systems.

Operation of the facility is similar to the trisonic leg. A flexible plate nozzle is set to the desired Mach number and the adjustable diffuser is set to an optimum setting. While these preparations and the necessary model work are going on, a steel matrix electric induction storage heater is being brought to the desired temperature. Upon initiation of the blowdown cycle, air is brought from the 5000 psia (3450 N/cm^2) storage tanks, throttled to the set-point stagnation pressure, and admitted to the stilling chamber. Five blowdown lines are provided, but there is only one heater. For temperatures less than the maximum 800°F (426°C), cold air is mixed with the hot air in a special mixing chamber at the entrance to the stilling chamber. Ejectors are used to ease starting loads, as in the transonic/supersonic leg, and to permit testing at low Reynolds numbers.

The safe operation of this test leg will require that specific operation procedures and permissive circuits be developed to assure protection of personnel and equipment. The primary personnel safety concerns and preventative measures are summarized in Section 2.0. This test leg does not present any unusual safety problems as regards to personnel.

Discussion of the design features of the test leg components, problem areas, safety considerations, and construction technology follows:

(a) Pressure Shell - The pressure shell is comprised of the hot air mixer section, stilling section, main pressure shell, and ejector constant diameter mixing section.

The mixer configuration is similar to that developed for use at AEDC for a large test facility. Utilizing a mixer allows testing over a wide range of temperature and mass flow conditions with the minimum heater size. Hot air enters the mixer through an interchangeable heater back pressure nozzle. Four cold air lines enter the mixer at an expansion section, the cold air being injected at 90° to the hot flow stream. A mixing section of approximately three to four diameters in length housing a flow disperser provides uniform flow to the nozzle entrance. The design details of this type mixer are currently known, with prototype testing experience available. This will eliminate the need for additional development to confirm design details. The operating procedures and characteristics of this specific hardware can be determined and confirmed during the facility shakedown operations or in a mock-up situation prior to facility installation.

A flow disperser is mounted near the downstream end of the mixer to smooth the flow entering the stilling chamber nozzle entrance area. This hardware must take quite large and possibly nonuniform loads. The downstream end of the mixer and stilling chamber must be fitted with adequately sized pressure relief valving to relieve inadvertent overpressurization. Access to the mixer and stilling chamber areas must be provided for inspection and maintenance of the mixer, flow disperser and adjustable nozzle throat block. Emergency stop switches and access hatch interlock keys should be provided to prevent tunnel start or operation with personnel in this area.

The 18-foot (5.5 m) diameter pressure vessel contains the adjustable nozzle, test section and adjustable diffuser hardware. Construction is standard practice, the shape being circular, with exterior stiffening rings and interior bulkheads and framework supporting the flexible plate nozzle, test section, and adjustable diffuser. Except for the mixing section, and stilling chamber, the shell is constructed to withstand an internal pressure of ± 15 psig (10.3 N/cm^2). The stilling chamber and mixing section are designed to a pressure of 2500 psi (1720 N/cm^2). The 18-foot diameter main pressure shell is approximately 165 feet (50 m) long and will require field fabrication and erection. The associated equipment and procedures discussed in Section 2.5 will apply. The vessel will be equipped with pressure relief systems in case of seal or structural failures.

Facility thrust and expansion are handled utilizing anchors at the heater, mixer and ejector mixing section stations, and flexible seals near the ejector station and at the muffler. Wheels attached to the various tunnel components operating on trackage support and align the facility and allow for longitudinal facility growth. In general, all components of the pressure shell consist of large versions of existing high pressure construction so a confidence level of 4 is assigned.

(b) Control Valves - The primary tunnel airflow is handled from storage through five 16-inch (40 cm) pipelines with a working pressure of 5000 psia (3450 N/cm^2). Stagnation pressure control is achieved utilizing control valves in each of the lines. Four of these lines go directly to the mixer and the remaining line goes to a storage heater which in turn pipes hot air to the mixer. The reasons for selecting multiple control valves for this test leg are identical to those for the trisonic leg. In addition, stress considerations dictate the use of a number of small diameter pipes of reasonable wall thickness rather than one large pipe with a wall thickness greater than four inches (10 cm). Fabrication and on-site erection considerations also favor the use of multiple blowdown lines and control valves.

A large number of control valve operating configurations are available, utilizing the heater and mixer combination. The control valves will utilize an automatic control system which can be preprogrammed to yield the correct mixed air temperature. This control system will be an integral part of the interlock system. Certain safety precautions will be necessary regarding the valving between the high pressure air storage and the wind tunnel (and personnel working areas) to prevent inadvertent pressurization of the test leg in the event that the upstream isolation valving should fail. If the control valves are not tight shutoff it is recommended that an isolation valve also be installed at the downstream end of the 16 inch (40 cm) pipelines upstream from the control valves. Control valves of this size and pressure rating have been constructed and operated, so a confidence level of 5 is assigned.

(c) Flexible Nozzle Assembly - The 12 foot (3.66 m) adjustable nozzle sidewall consists of a cam operated throat block and a flexible plate positioned with screw jacks with a sliding seal at the downstream end of the nozzle. The basic design concept utilized in this nozzle is similar to that previously used in AEDC Tunnel E. This nozzle design is significantly larger than that at AEDC and is further complicated from a materials and sealing standpoint due to the flow temperature conditions. One of the major design problem areas will undoubtedly be in the area of sealing the nozzle block and sidewalls. Normal sealing materials will fail at the maximum flow temperatures of this facility. The specifics of the design must therefore keep the seal at a cooler location or provide a means of cooling. In addition, the throat block will be exposed to high stagnation pressures and the mounting and framework must provide for handling and removing these loads. The flexible plate loads are transmitted through the positioning jacks to the jack support framework which is mounted to the 18-foot (5.5 m) diameter pressure shell. Special techniques and fabrication procedures will be necessary to fabricate and machine the 12-foot by 60-foot (3.66 x 18 m) nozzle plate. Careful consideration must also be given to the method of attaching the jacking pads to prevent damage to the base material. The attachment design of the flexible plat to the throat block is critical, as a smooth, continuous flow surface in this area is required at all positions of the adjustable nozzle.

Access to the adjustable nozzle throat block positioning and flexplate screw jack systems must be provided in the pressure shell for nozzle adjustments, maintenance and repair. Nozzle adjustment programs must be prepared and operational procedures developed to prevent damage to the nozzle during adjustment. The facility interlock systems should provide for verification that the nozzle configuration is correct and ready for running.

The access area for nozzle work must be protected with emergency stop switches and hatch interlocks to prevent tunnel operation and hazards to personnel who may be within the pressure shell.

The flexible nozzle assembly, because of its size and temperature problems, is assigned a confidence level of 3.

(d) Test Section - A 12 x 12 foot (3.66 m x 3.66 m) test section 18-feet (5.5 m) long will accommodate models up to 12-feet long. A model support sector and sting system provide model angle of attack capability in the range between -5° and 30°. As envisioned in this design concept, the sting will travel along the sector utilizing a drive motor which engages a gear on the backside of the sector. Five large slot type schlieren windows provide viewing of the model. The windows are located between the steel test cabin support members. Access for model hardware is assumed through a top hatch in the test section pressure shell. A personnel hatch is provided on the side of the test section.

The desi[illegible] fabrication, and operational problems associated with the model support, pitc[illegible] [illegible]hanism and balance hardware are problems directly related to the relative size o[illegible] this equipment. The run time of the facility, being short, will require that the pitch mechanism travel at a fairly high rate to cover the pitch envelope. Considering the weight of the balance, sting, and model system, the drive motor may become large. A means shall also be provided to take the balance leads and any model services out of the model support system.

An alternate test section arrangement, not shown, which should be seriously considered in a design study, is the use of a partial test section cart. This concept, as used by the Swedish FFA in one of their facilities, consists of having the rear p[illegible] of the test section, containing the model support, be removable from the test leg intact as a unit. The advantages are the same as mentioned for the trisonic test carts, namely, test utility improvement by reduction of tunnel occupancy time. Disadvantages are the need for at least two such partial carts and model supports.

Viewing windows of the size required in schlieren quality material may require fabrication technique development. The mounting of large windows also presents problems of sealing and differential expansion. Extreme care must be taken in the design and installation to prevent overstressing the windows.

Certain operational interlocks will be required to protect the model and model support systems. A balance overload interlock should be incorporated to prevent further operation if the balance loads exceed a predetermined value. Interlocks should be incorporated which will terminate a run if the model support drive motor should lose power or any of the model or model support services such as cooling water or air should malfunction.

Personnel safety consideration in the test section will probably be primarily involved with the handling of equipment and standard industrial safety requirements would apply. This section must, however, be interlocked with emergency stop switches to protect personnel inadvertently left in the test area. The tunnel hatches must be interlocked to prevent operation with open hatches. In general, problems of design of the test section components relate mainly to their size, so a confidence level of 4 is assigned.

(e) Adjustable Diffuser and Ejectors - The mode of operation for this facility will require the use of main stream air ejectors to obtain the required tunnel starting pressure ratio. Once flow is established, the adjustable diffuser is actuated to a predetermined position to reduce the running pressure ratio requirements. As mentioned for the transonic/supersonic diffuser, careful consideration must be given to the actual need for adjustment of the diffuser while running, balancing the lower stagnation pressures and longer run times obtained versus the more powerful actuators and complex controls required.

The adjustable diffuser features sliding supports at both extremities which permits vertical screw jack motion without pivots. The screw jack mechanism is mounted externally to the pressure shell to avoid increasing the shell diameter. A sliding seal in the adjustable diffuser seals against the sidewall. The screw jacks are motor driven with an automatic control system to a predetermined closing, dependent upon the test conditions, and this preset closing program should be incorporated into the interlock system to prevent running prior to verifying the program. Interlocked access to the diffuser through the pressure shell will be necessary for maintenance and inspection of diffuser seals, jack system connections and sliding supports.

The nine supersonic flow ejectors are located downstream of the diffuser transition section in the flow channel. A single automatically controlled valve upstream of the ejector manifold regulates the ejector flow pressure. This automatic ejector control will be programmed to maintain a preset ejector nozzle pressure and will be interlocked to prevent inadvertent operation. The confidence level of the adjustable diffuser assembly and ejectors is 4.

(f) Muffler - Downstream from the ejector mixing section and subsonic diffuser, the flow enters a muffler to attenuate low and high frequency noise levels. The muffler assembly incorporates a perforated plate to attenuate low frequency noise, and high frequencies are handled in the tube type vertical exhaust stacks (for reference see Appendix A). The primary structure is reinforced concrete. Safe access to the muffler for inspection and maintenance should be provided, utilizing emergency stop switches and access door interlocks to prevent operation if the hatch is open or the switch is in the stop position. The muffler is assigned a confidence level of 5.

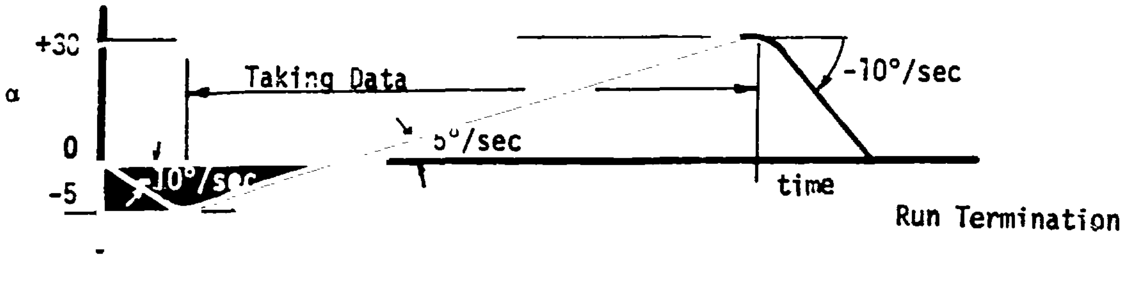
Cost of the hypersonic test leg including the main control valves is estimated at $11,838,000. A breakdown of this cost estimate is presented in tabular form in Section 4.2.6.

The confidence level of this test leg is 4.6 based on the weighted average of the component confidence levels.

4.2.3 STORAGE VOLUMES, BLOWDOWN LINES - Two very large air storage tank systems are required for operation of the two test legs. The development in Section 6.2.6 of the Phase II final report gives the derivation of the relationship between minimum storage volume and facility maximum mass flow and minimum run time. These relationships were worked out for three cases: (I) Constant stagnation temperature, (II) No control of T_O (T_O drops according to a polytropic relationship with P_O), (III) Tank provided with a thermal matrix. All of the cases were solved using the ground rules of constant stagnation pressure and allowable Reynolds number change (owing to T_O change) during a run no greater than 7%. Minimum storage pressures are determined by calculating the final tank pressure at the end of the maximum mass flow run and at the end of the maximum pressure run. Frictional pressure drops must be included to determine the minimum initial storage pressure.

Minimum facility run times and mass flow rates were calculated in order to specify only the minimum volume and pressure required, but yet have enough air to satisfy the requirement of one full pitch or yaw cut per run.

The minimum run time was established using criteria developed from the MCAIR Polysonic Wind Tunnel experience. In that facility, experiments have been run to determine the maximum pitch rates at which force data will still be identical to data taken at fixed angles-of-attack. That is, inertial effects or dynamic flow effects must be negligible. It was found that, for the Mach range of .5 to 5.0, pitch rates well in excess of 5 degrees per second could be employed without deleterious effects on the force and moment data. Five degrees per second is the normal rate used for production testing in the PSWT, and is the rate adopted here for data taking. Ten degrees per second is used for moving the model from 0° to its initial data point angle and for returning the model to 0° from its final data point. The model pitch schedule assumed, then is:



In order to figure total air requirements, it is also necessary to define the time required for the ejectors to pump the facility down (t_{ej}), and time required to fill the stilling chamber to the set-point pressure and establish steady flow (t_{fill}). Again, from the MCAIR PSWT experience, these times were taken to be:

$t_{ej} = 3$ sec
$t_{fill} = 2.5$ sec

It is assumed that the main control valves are opened as soon as the ejectors have pumped the tunnel down, and are shut down when the model reaches +30°, the ejectors continuing until the model returns to 0°. The total air needed is:

$$W = W_1 \left[t_{ej} + t_{fill} + \Delta t_{\ 0^\circ \text{ to } 0^\circ}\right] + W_2 \left[t_{fill} + \Delta t_{\ 0^\circ \text{ to } 30^\circ}\right]$$

Where W_1 = ejector flow rate and W_2 = tunnel flow rate

or $W = W_1 \,[16.13] + W_2 \,[10.12]$

The ejector mass flows were calculated and using the maximum mass flow case for each test leg, the minimum stored mass, pressure, and volumes were calculated. Total air storage requirements are:

Total Volume	= 825,000 ft^3 (23,200 m^3)	For trisonic test leg (no thermal matrix, no in-line heater)
Max. Pressure	= 600 psia (414 N/cm^2)	
Max. Temp.	= 200°F (93°C)	
Total Volume	= 25,400 ft^3 (720 m^3)	For hypersonic test leg (in-line heater)
Max. Pressure	= 5000 psia (3450 N/cm^2)	

The total storage requirements were translated into hardware specifications. General layout of the tanks is shown in Figure 4-1.

The costs associated with the air storage system are as follows:

<u>Low Pressure System</u>

60 spherical tanks, 30 ft (9.2 m) dia., 3.875 in. (10 cm) wall thickness, grouped on 3 stands

$25,751,000

Pressurization lines from compressor plant, manifold piping, isolation valves, and safety burst diaphragms.

$ 246,000

Blowdown lines to facility and ejectors, 70 in. (1.78 m) I.D., 1.75 in. (4.45 cm) wall thickness, footings, supports, line isolation valves.

<u>$14,694,000</u>

Low Pressure System Total $40,691,000

High Pressure System

240 cylindrical tanks, 18 in. dia. (46 cm) and 60 ft (18.4 m) long, 3.5 in. (8.8 cm) wall thickness, arranged in 5 groups. Each group has 48 tanks and has 3 tiers of 16 tanks. Total volume is 25,650 ft^3 (725 m^3).

$ 9,609,000

Pressurization lines from compressor plant, manifold piping, tank isolation valves and burst diaphragms.

$ 333,000

Blowdown lines to stilling chamber and ejectors, 16 in. (40.6 cm) I.D. and 3 in. (7.6 cm) wall thickness, footings, supports, line isolation valves.

$ 5,328,000

High Pressure System Total $15,270,000

The number of tanks, their dimensions, and shape were based on advice from Nooter Corp. It is felt that although this is a very large and costly system, the individual components are within current technology. The wall thicknesses necessary, however, are near the limit of construction practice. The large isolation valves are in the same category. Therefore, a confidence level of 4 is assigned to the entire air storage system.

4.2.4 COMPRESSOR PLANT - Redefinition of the total air requirements for each test leg as described in 4.2.3 also resulted in reduced compressor requirements. Keeping the original goal of maximum run turnaround time equal or less than two hours results in a new compressor specification:

Q = 100,000 cfm (2832 m^3/min) at P_{inlet} = 14.2 psia (9.8 N/cm^2)
T_{inlet} = 90°F (32.3°C)

P_{outlet} = 600 psia (413 N/cm^2) .... Low Pressure Tanks
5000 psia (3450 N/cm^2) ...... High Pressure Tanks

Dewpoint = -60°F (-51°C)

This plant is a relatively simple plant since it is not required to run over a wide range of volume flows and pressure ratios. These requirements were given to Allis Chalmers, who have specified a compressor plant.

A schematic of the plant arrangement and a bill of material included are shown in Figure 4-6. The plant contains five stages of compression. Low pressure air for the trisonic test leg is obtained from the second stage. The last three stages are required to obtain 5000 psia (3450 N/cm^2) for the hypersonic test leg. The cost of this plant is broken down as follows:

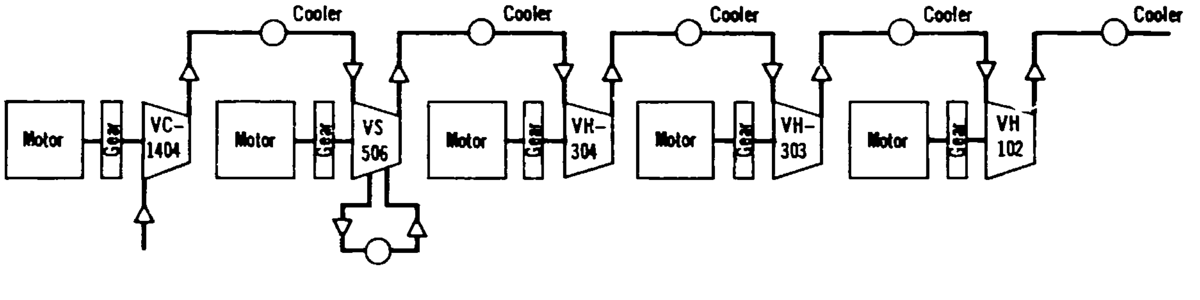
Mechanical Components: Including all equipment listed on the bill of material, plus installation and setup charges

		$ 9,794,000
Building and Foundation		812,000
	Total	$10,606,000

If the facility is constructed at AEDC, a cost saving may be made by using the existing capability of the VKF compressor plant. Using this scheme, atmospheric intake at the VKF 3rd stage is used. The low pressure tanks receive air from the 5th stage. One machine must be added to the existing plant to boost from 4000 (2760) to 5000 psia (3450 N/cm^2). The cost of this addition, including installation, extra dryer capacity, footings, interconnecting piping and valves is $1,225,000. Balanced against the potential cost saving is the cost of extra piping runs from the VKF plant to the location of the facility and the fact that the compressor would be shared among all the VKF facilities and the two test legs of GD20.

The compressor plant, whether new or a modified existing plant, is comprised entirely of existing and available equipment, both in size and performance. It has a confidence level of 5.

FIGURE 4-6
GD20 COMPRESSOR PLANT
Schematic of Plant Layout



Compressors Required

Type Compressor*	VC-1401	VS-506	VH-304	VH-303	VH-102
Inlet Volume - cfm(m^3/min)	1000,000 (2830)	12,500 (353)	2400 (68)	830 (23.5)	435 (12.3)
Inlet Pressure - psia(N/cm^2)	142 (9.8)	113 (78)	590 (406)	1730 (1190)	3280 (2270)
Disch Pressure - psig(N/cm^2)	125 (86)	620 (438)	1830 (1260)	3460 (2390)	5000 (3450)
Power - hp(kW)	18,600 (13,900)	16,100 (12,000)	12,000 (8900)	7250 (5400)	4529 (3370)

Utilities Summary

Total Compressor Power - hp(kW)	58,000	(43,200)
Cooling Water Requirements - gpm(m^3/min)	15,000	57
Water System Power - hp(kW)	3,000	2,240
Hydraulic System Power - hp(kW)	5,000	3,730
Total Power - hp(kW)	66,000	49,170

Bill of Material

Compressors	Switch Gear	Dryers
Motors	Control Center	Water Pumps
Sole Plates	Transformers	Cooling Tower
Lube Systems	Anti-Surge Control	Compressor
Coolers	Interconnecting Piping and Valving	Evacuation System
Gears		

*Allis Chalmers Model Number

4.2.5 HEATERS - Both test legs require the addition of heat to the airstream in order to avoid liquefaction at the higher Mach numbers. An oil or gas-fired heat exchanger will be used for the transonic/supersonic test leg and a steel matrix induction storage heater is used for the hypersonic test leg.

(a) Gas or Oil-fired Heat Exchanger - This heat exchanger is installed in the line from the compressor plant to the low pressure storage tanks. The heated air is stored in the tanks. This heater is used only when testing above Mach 3. Specifications of this heat exchanger are:

Max. Air Pressure	600 psia (413 N/cm^2)
Max. Air Temperature.	500°F (270°C)
Max. Air Flow Rate.	116 lb/sec (53 kg/sec)
Heating Rate.	80 x 10^6 Btu/hr (84 x 10^9 Joules/hr)
(Efficiency assumed = 50%)	

Heat exchange units of this type are commonly used in wind tunnel facilities and present no unusual design or construction problems. A confidence level of 5 is assigned. The cost is estimated to be $800,000.

(b) Electric Induction Storage Heater - This heater is placed in one of the five blowdown lines. It is a storage heater, a bundle of steel tubes serving as the heat storage matrix. This type of heater, although not common in current wind tunnel operations, has been proven feasible at Lewis Laboratory and is common in other industrial practices. The design of this component can be handled by drawing on experience of the existing operational hardware and should not require development to achieve a workable system. The heater is blown down from top to bottom with the hot air exhausting through the grate support into the mixer. Utilizing this configuration eliminates the need for a heater pit as the heater is supported on a concrete pad above ground.

The design and fabrication problems anticipated in regards to the heater will fall within the details of the electric reheat system, i.e., the design and fabrication of the electric coils, the terminal connection which penetrates the vessel, the electrical coil support and insulation within the heater shell and the special requirements of the coil cooling water system. None of the above details are beyond current design or fabrication technology.

Several electric circuits are incorporated to allow reheating of various sections of the matrix to obtain the desired blowdown temperature profile. The heater will be instrumented with thermocouples. The electrical system and power generation for the reheat system are of a size which requires precise controls and procedures to assure the safety of working personnel. During reheat, the heater should be vented to prevent hot air from being discharged into the tunnel components. In addition, the electrical control system must provide for continuous monitoring of the coil water cooling, matrix, grate and shell temperatures. This reheat control system must be fail safe in that coil electrical malfunctions, loss of coil cooling water or overtemperature conditions in any heater component will automatically shut down electrical power. The blowdown operation will require that the heater be fitted with pressure relief valves to prevent over-pressurization.

Specifications of the Heater are:

Max. Air Pressure . . . . 3000 psia (2070 N/cm^2)
Max. Outlet Air Temperature . . . . . . 800°F (427°C)
Max. Flow Rate. . . . . 11,000 lb/sec (5000 kg/sec)
Heater Input Power . . . . 2.5 megawatts

The cost of the induction heater is estimated to be $1,817,000 and a confidence level of 3 is assigned.

4.2.6 COST SUMMARY - Figure 4-7 presents a detailed cost breakdown for the GD20 facility, based on the costing technique presented in Section 2, as necessary to acquire the entire facility. Figure 4-8 presents a similar cost breakdown for the facility integrated into the AEDC 16S/16T complex.

The contributions of the components to the total cost can best be illustrated by Figures 4-9 and 4-10. In the basic facility the compressor plant does not represent a dominating cost factor, so integration of GD20 into an existing complex, such as AEDC, to utilize compressor plant capability does not have a substantial cost savings. The transonic test carts were not deleted in the AEDC integrated facility because, although interchangeable with existing 16S/16T carts, the acquisition of GD20 would require that two additional carts be manufactured. The net saving by integration is then about 14 million dollars compared to a total investment cost of 146 million dollars. The dominance of the air storage system is clearly shown, as well as the greater costs associated with the trisonic test leg compared to the hypersonic leg. This cost compares favorably to existing facilities in terms of the funds required to provide additional experimental research capability. AEDC 16S/16T represented a major increase in the testing capability in large, continuous transonic and supersonic wind tunnels. Flexible plate nozzles, and porous walled transonic test sections of a magnitude never before attempted were realized in the design of these facilities. Their cost in terms of 1970 dollars would be about 250 million dollars, to provide a Mach number capability to Mach 5. GD20, an intermittent facility, provides about 4 times the Reynolds number capability of these continuous facilities to Mach number 8.5 at about one-half their cost.

Although a major cost advantage is not apparent by integration with AEDC, their experience in operating very large facilities of this type with interchangeable test section carts, flexible plate nozzles, and large compressor plants could materially aid in minimizing the problems associated with equipment integration as the facility is brought into operation. For that reason, AEDC is considered a very attractive location for such a facility. Other aspects of this are discussed in Sections 4.3 and 4.4.

The operating costs were estimated based on the ground rules presented in Section 2.3.2, using the following assumptions.

(a) The compressor plant, and associated equipment runs at its maximum capacity during an operating shift, therefore the power utilization factor is:

$$U_P = 1.0$$

FIGURE 4-7
COST SUMMARY – GD20

Facility Component	Cost ($1000's)
Test Leg, Trisonic	
Footings and foundations	596
Pressure shell	5,596
Flow spreader	478
Stilling chamber screens	20
Flexible plate nozzle	3,033
Transonic test cart	3,250
Supersonic test cart	2,500
Ejector, transonic	96
Ejector, supersonic	23
Adjustable diffuser and mechanism	412
Muffler	2,156
Subtotal Test Leg, Transonic	15,560
Test Leg, Hypersonic	
Footings and foundations	326
Cold Air Inlet Pipes	556
Venturi	79
Pressure shell	1,023
Flow spreader	204
Stilling chamber screens	7
Flexible plate nozzle	721
Test cabin including schlieren windows	440
Model support system	150
Ejector	15
Adjustable diffuser and mechanism	264
Muffler	1,233
Subtotal Test Leg, Hypersonic	5,018
Induction Heater (For Hypersonic Leg)	
Cold air pipe	246
Heater shell and foundation	522
Shaded pole structure	7
Induction coils	300
Thermal insulation	265
Heater tubes (steel matrix)	189
Hot air pipe	250
Development cost	38
Subtotal Induction Heater (For Hypersonic Leg)	1,817
Oil/Gas Fired Heat Exchanger	800

FIGURE 4-7 (Continued)
COST SUMMARY – GD20

Facility Component	Cost ($1000's)
Compressor Plant	
Building	812
Compressor	9,794
Piping (to storage tanks)	60
Control valves	519
Subtotal Compressor Plant	11,185
Air Storage (Low Pressure)	
Storage tanks	25,751
Piping (to transonic test leg)	3,825
Control valves	17,669
Subtotal Air Storage (low Pressure)	47,245
Air Storage (High Pressure)	
Storage Tanks	9,609
Piping (to hypersonic test leg)	1,458
Control valves	10,690
Subtotal Air Storage (High Pressure)	21,757
Test Section Shelter	835
Laboratory and Office Building	450
Model Assembly Building	2,438
Substation	1,440
Hydraulic Power Supplies	1,005
Automatic Control System	
Trisonic Leg	800
Hypersonic Leg	800
Subtotal Automatic Control System	1,600
Instrumentation and Data Acquisition	
Trisonic Leg	5,800
Hypersonic Leg	3,680
Subtotal Instrumentation and Data Acquisition	9,480

FIGURE 4-7 (Continued)
COST SUMMARY – GD20

Facility Component	Cost ($1000's)
Total GD20 Components	120,630
Contingency @ 10%	12,063
Total GD20 Facility Cost	132,693
A&E Fee @ 6%	7,950
Management & Construction Coordination Fee @ 4%	5,300
Grand Total GD20	145,943

FIGURE 4-8
COST SUMMARY – GD20 INTEGRATED AT AEDC

Facility Component	Cost ($1000's)
Test Leg, Trisonic	
Footing and foundations	596
Pressure shell	5,596
Flow spreader	478
Stilling chamber screens	20
Flexible plate nozzle	3,033
Transonic test cart	3,250
Supersonic test cart	2,500
Ejector, transonic	96
Ejector, supersonic	23
Adjustable diffuser and mechanism	412
Muffler	2,156
Subtotal Test Leg, Transonic	15,560
Test Leg, Hypersonic	
Footings and foundations	326
Cold air inlet pipes	556
Venturi	79
Pressure shell	1,023
Flow spreader	204
Stilling chamber screens	7
Flexible plate nozzle	721
Test cabin including schlieren windows	440
Model support system	150
Ejector	15
Adjustable diffuser and mechanism	264
Muffler	1,223
Subtotal Test Leg, Hypersonic	5,018
Induction Heater (for Hypersonic Leg)	
Cold air pipe	246
Heater shell and foundation	522
Shaded pole structure	7
Induction coils	300
Thermal insulation	265
Heater tubes (steel matrix)	189
Hot air pipe	250
Development cost	38
Subtotal Induction Heater (for Hypersonic Leg)	1,817
Oil/Gas Fired Heat Exchanger	800

FIGURE 4-8 (Continued)
COST SUMMARY – GD20 INTEGRATED AT AEDC

Facility Component	Cost ($1000's)
Compressor Plant	
Building	-
Compressor	1,225
Piping (to storage tanks)	60
Control valves	519
Subtotal Compressor Plant	1,804
Air Storage (Low Pressure)	
Storage tanks	25,751
Piping (to transonic test leg)	3,825
Control valves	17,669
Subtotal Air Storage (Low Pressure)	47,245
Air Storage (High Pressure)	
Storage tanks	9,609
Piping (to hypersonic test leg)	1,458
Control valves	10,690
Subtotal Air Storage (High Pressure)	21,757
Test Section Shelter	835
Laboratory and Office Building	450
Model Assembly Building	-
Substation	1,440
Hydraulic Power Supplies	1,005
Automatic Control System	
Trisonic leg	800
Hypersonic leg	800
Subtotal Automatic Control System	1,600
Instrumentation and Data Acquisition	
Trisonic leg	5,800
Hypersonic leg	3,680
Subtotal Instrumentation and Data Acquisition	9,480

FIGURE 4-8 (Continued)
COST SUMMARY – GD20 INTEGRATED AT AEDC

Facility Component	Cost ($1000's)
Total GD20 Components	108,811
Contingency @ 10%	10,881
Total GD20 Facility Cost	119,692
A & E Fee @ 6%	7,180
Management and Construction Coordination Fee @ 4%	4,799
Grand Total GD20	131,661

FIGURE 4–9
DISTRIBUTION OF FACILITY ACQUISITION COSTS – GD 20

Total Acquisition Cost: $145,943,000

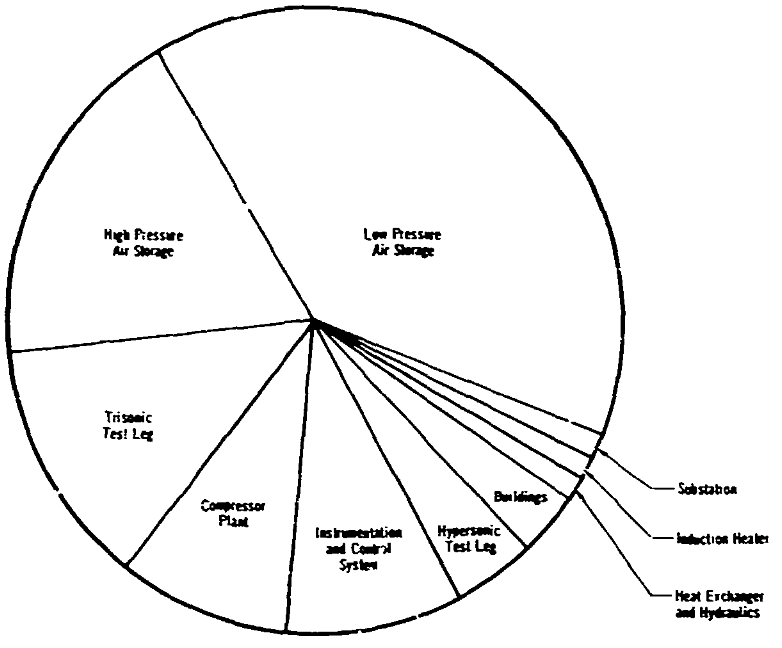
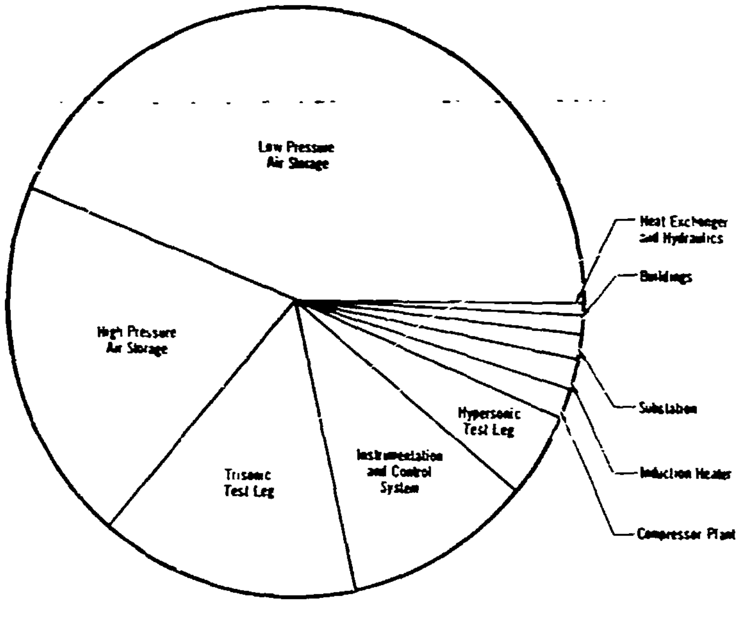


FIGURE 4–10
DISTRIBUTION OF FACILITY ACQUISITION COSTS – GD 20 INTEGRATED AT AEDC

Total Acquisition Cost: $131,661,000



(b) The run utilization factor is 0.9 for each leg, but the compressor plant is shared by two legs, so that effective run utilization factor (U_R) is:

$$U_R = 0.45$$

(c) The facility utilization factor (U_f) is:

$$U_f = 0.80$$

(d) The staff directly charging to the facility is 50 people per test leg.

(e) The annual maintenance cost was based on the assumption that the compressor plant would represent a major portion of the maintenance costs. Costs were based on data supplied by AEDC on the operation of the VKF compressor plant, and to account for the other maintenance items the compressor plant maintenance costs were doubled. This cost includes only parts and equipment, manpower charges being included in the 50 people per leg staffing.

Annual maintenance costs, both legs $130,000

Utilizing these factors, the cost equations given in 2.3.2 were evaluated. The cost per tunnel occupancy hour per test leg is then:

Power	210	
Staff	1250	
Maintenance	65	
Total	$1525	per occupancy hour for each test leg

4.3 SPECIFIC SITE CONSIDERATIONS

In addition to the general site considerations in Section 2.7, GD20 poses problems in two additional areas, namely, the potential noise associated with its operation, and the shipment of outsized subassemblies to the site for field fabrication.

Although the muffler concept was based on a design which met community noise ordinances (Appendix A), its design mass flow was about 2000 lb/sec (906 kg/sec). The maximum mass flow for GD20 is about 88,000 lb/sec (40,000 kg/sec), and although it should be possible to maintain similar noise levels, the discharge of that quantity of air could pose additional problems. In order to prevent a possible protracted delay and potentially increased costs due to unanticipated noise problems, a remote site, away from major population centers, would probably be desirable.

The shipment of outsized subassemblies for field fabrication would require that adequate rail and road access be available. The proximity of a navigable waterway could reduce shipping costs and improve the size of components which could be shipped to the site.

Although as shown in the cost section (4.2.6), the cost advantages of integrating into the 16S/16T complex at Arnold Engineering Development Center are not large, the fact that a wind tunnel facility of similar size and complexity has already been constructed at that site adds to its potential as a suitable site. The removable test section carts of the trisonic test leg have been specified to be interchangeable with those of the AEDC 16T and 16S PWT facility, enabling tests on the same model to be run in any of these facilities without excessive installation times. Also, the experience of that organization in operating very large components, such as the flexible plate nozzle system should reduce the uncertainties associated with bringing any facility of this size and complexity into operation. Although other existing facility complexes could accommodate GD20, the availability of navigable waterways in proximity to AEDC, the remoteness of the Arnold Air Force Station with respect to population centers, and the availability of personnel with immediate experience in the design, fabrication, checkout, and operation of similar wind tunnel facilities would seem to present the least hostile environment for the construction and operation of a major new facility such as GD20

4.4 DEVELOPMENT ASSESSMENT

The general rules for the development assessment are presented in Section 2.4. Individual component assessments are contained in each subsection discussion of the facility components, and will be summarized in this section. The following table lists the individual facility element, cost fraction, confidence level evaluation, and technical risk ranking.

Item	Cost fraction (K_i)	Confidence level (C_{L_i})	K_i C_{L_i}	Percent technical risk	Technical risk ranking
Trisonic test leg	.106	4.1	.435	10.92	3
Hypersonic test leg	.035	4.6	.161	2.66	6
Air storage system	.480	4.0	1.920	52.20	1
Compressor plant	.081	5.0	.405	4.41	5
Combustion heater	.005	5.0	.025	.27	7
Induction heater	.125	3.0	.375	20.40	2
Balance of equipment	.168	5.0	.841	9.13	4
Total	1.00		4.16	100.00	

The numerical confidence level associated with the development assessment of GD20 is equal to 4.16. This numerical evaluation is consistent with a subjective evaluation that GD20 represents a larger version of equipment currently in operation, as based on the definitions contained in Section 2.4.

The low development risk associated with this facility implies that although large in size, it does not represent a major challenge to the current fabrication technology level. As shown, the major risks would be associated with the large, high pressure air storage system and the induction heater. The operating principles of GD20 have been well developed in several moderate sized, industry owned blowdown wind tunnels. Certain design details of the test legs should be confirmed and optimized by small scale prototype development. For the trisonic test leg, these areas are:

1) Stilling chamber design details, particularly the inlet manifold design and flow disperser and screens. Flat velocity profiles and low turbulence in this area under all conditions of mass flow and valve configuration are essential for the development of good test section flow. 2) Confirmation of the operating characteristics of the transonic ejectors, the ejector flow re-entry to the main flow, and the supersonic ejectors. For the hypersonic test leg, the prototype electric induction heater design details and operating characteristics should be investigated on a small scale before commitment to final design.

In summary, although both test legs are relatively large, the facility incorporates well tried operational techniques and common construction methods, and is capable of attaining its performance goals with very low risk.

4.5 ACQUISITION SCHEDULE AND TIMING

The schedule for acquisition of GD20 is presented in Figure 4-11 and is based on the general considerations given in Section 2.8. It is seen that the facility can be available for use in a little over six years.

The 6-1/8 year acquisition schedule is reasonable for a facility of the size and capability of GD20. Some time elements could be reduced if the program was conducted on a crash basis, but the proposed schedule is conservative and allowance has been made for the usual slippage on a major facility effort. The total period of 12 months from completion of construction to the end of initial calibration embraces facility demonstration tests as well as calibrations and may be longer than would be allowed under the pressure of test program schedule demands. Still, this time should be spent before routine test programs are scheduled. The cost and schedule for acquisition of the complete facility are then:

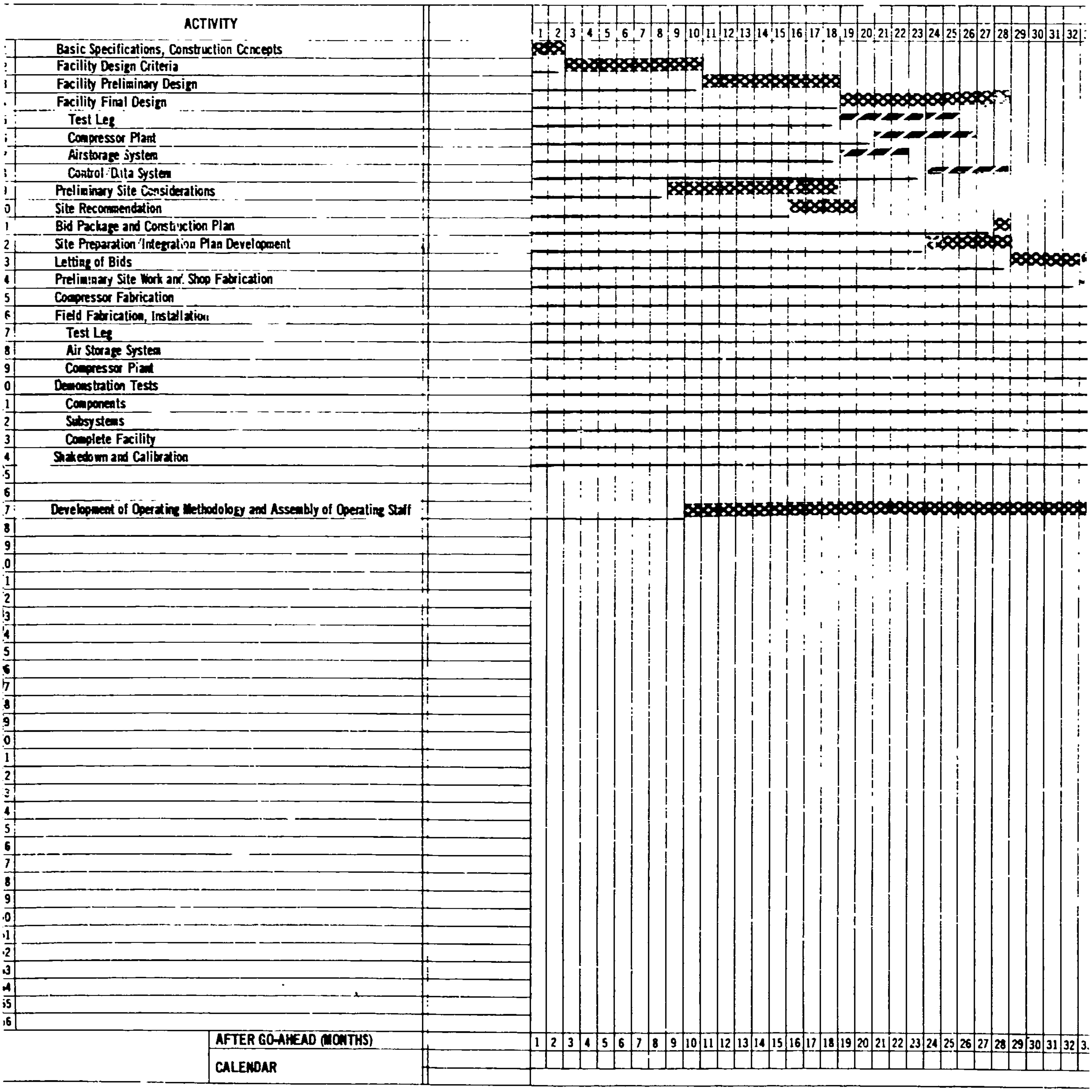
Cost - - - - - - - - - - - - - - -	$145,943,000
Schedule - - - - - - - - - - - - -	74 months

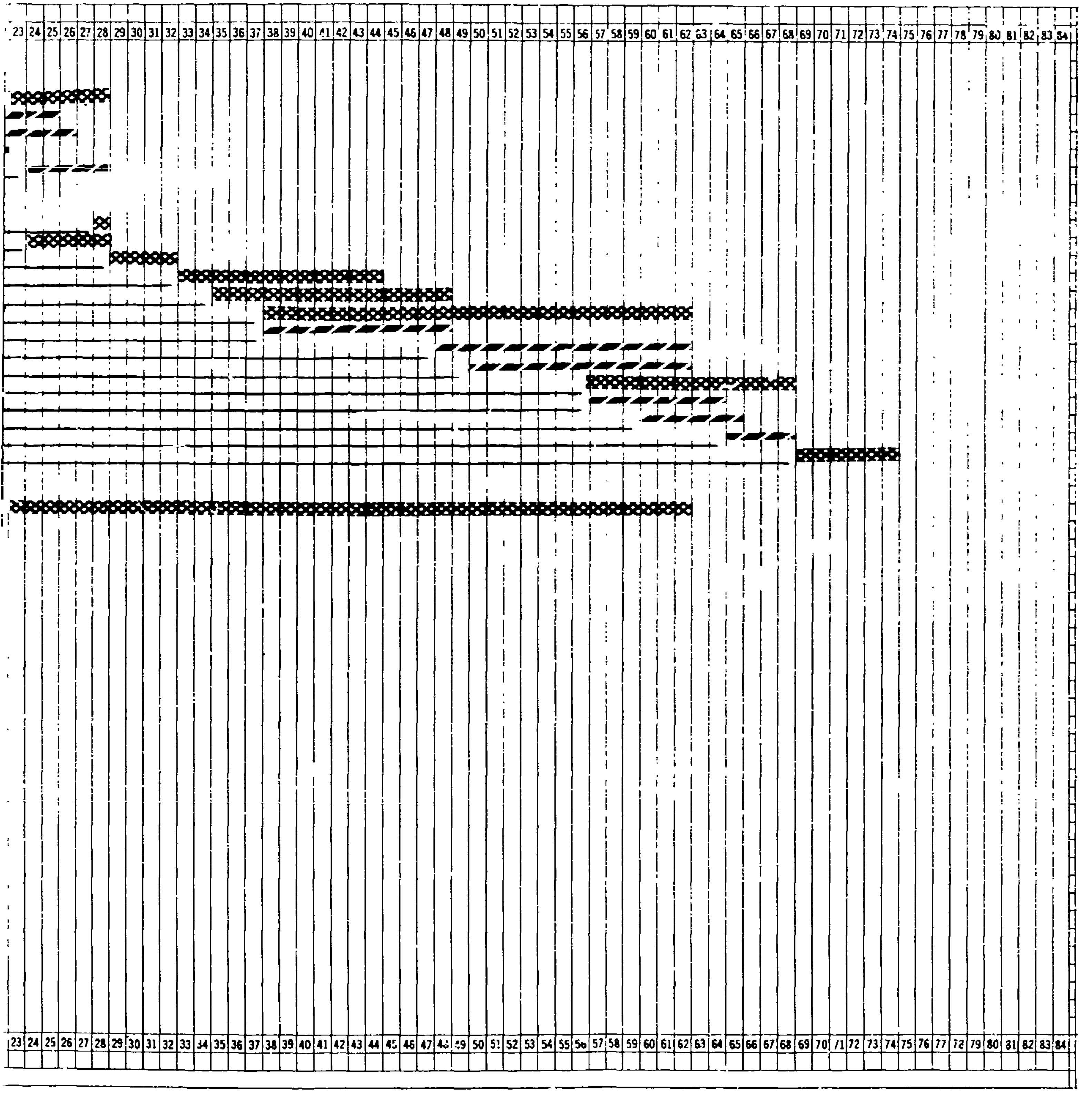
At the expense of increasing total costs, the annual costs can be reduced by employing a stretched-out program where the initial facility performance capability is less than the final goal. This requires sufficient planning so that additional performance increments can be added without significant interruption of the basic facility operation.

The primary alternative available for GD20 is to construct the hypersonic test leg at some time after the trisonic test leg. The complete building for the compressor plant can be initially constructed to accommodate the final number of machines. Since the compressors for the hypersonic leg require a portion of the output from the compressors for the trisonic leg, provisions should be made to add these compressors at a later date without seriously interrupting the operation of the trisonic leg. Adding the hypersonic test leg at a later time would reduce the initial acquisition cost by the amount required for the air compressor, valves, test leg, muffler, and air storage tanks. Since a common control room and data acquisition system building is envisioned, it is assumed that this building would be built in nearly final form. The cost and schedule alternatives are then:

Cost	
Trisonic Leg Initially Acquired - - - - - - - - -	$105,949,000
Hypersonic Leg Acquired at Later Date - - - - - -	$ 52,000,000
Total - - - - - -	$157,949,000
Schedule	
Trisonic Leg Initially Acquired - - - - - - - - -	66 months
Hypersonic Leg Requiring an Additional - - - - - -	36 months
Total - - - - - -	102 months

FIGURE 4-11
ACQUISITION SCHEDULE, GAS DYNAMIC RESEARCH FACILITY - GD20





FOLDOUT FRAME 2

4.6 EVALUATION SUMMARY

The Polysonic Wind Tunnel is an aerodynamic simulator, providing duplication of local Reynolds numbers in the Mach number range of 0.5 to 8.5. Stagnation temperature sufficient only to avoid air condensation in the test section is provided and no attempt is made to duplicate the actual flight environment.

In order to determine the magnitude of the required facility Reynolds number, the flight envelope encompassing the nine potential operational hypersonic aircraft was established. From this, the unit Reynolds number requirements, independent of size, could be determined. The flight envelope, and resulting Reynolds number corridor developed in Volume II are presented in Section 4.0. The nine aircraft presented in Volume VI can be grouped into three classes by their approximate lengths.

Length class, 300 ft (91 m) - - - - L1, L2, C1, also Space Shuttle
200 ft (61 m) - - - - L3, L4, C2, M2, M3
100 ft (30 m) - - - - M1, also Research Aircraft

The adequacy of the present experimental research capability was established by quantifying the unit Reynolds number corridor for these three characteristic lengths, and comparing requirements with existing facility capability. Examining the three graphs in Figure 4-12, the following conclusions were made.

- In terms of Reynolds number duplication requirements for the 100 foot (30 m) long vehicles, existing facilities can provide an acceptable degree of Reynolds number duplication ranging from complete duplication near the lower dynamic pressure boundary to about one-fifth the maximum Reynolds number at the high dynamic pressure boundary.

- For 300 foot (91 m) long aircraft, existing facilities can achieve duplicated Reynolds numbers at a few Mach numbers for the minimum dynamic pressure boundary. A serious deficiency in Reynolds number capability exists particularly at Mach number less than 3. Only 1/15 to 1/20 of the maximum Reynolds number, and 1/10 of the cruise Reynolds number can be obtained with existing facilities.

- For a 300 foot (91 m) long Space Shuttle vehicle, the opposite judgement appears valid. Full scale Reynolds numbers over all but a portion of the exit trajectory can be achieved in existing facilities. Although this vehicle was not one of the nine potential operational aircraft, it is presented to contrast the evaluations concerning the adequacy of existing facilities based on different operational concepts.

- For the 200 foot (61 m) length aircraft, the adequacy of existing research capability is not clear-cut. Although not providing the Reynolds number capability desired, existing facilities could be used to estimate the performance of an operational aircraft. The provision of additional Reynolds number capability would probably increase the confidence in predicted performance of the full scale vehicle.

The Reynolds number criteria established from the nine operational aircraft concepts as a design criteria for the gasdynamic facilities was 1/5 of the maximum Reynolds number corresponding to the maximum dynamic pressure for a nominal 300 feet (91 meter) aircraft. The 1/5 requirement was developed from data which was later published in Reference (1) which indicated this as an acceptable extrapolation interval to full scale values, employing current aerodynamic theory.

An additional factor in the judgements affecting the design criteria for the gasdynamic research facilities was that the simulation level selected for the facilities should represent a significant increase in Reynolds number simulation level over existing facilities, as well as satisfy the latter potential operational aircraft criteria. The performance envelope defined for GD20 satisfied both these criteria.

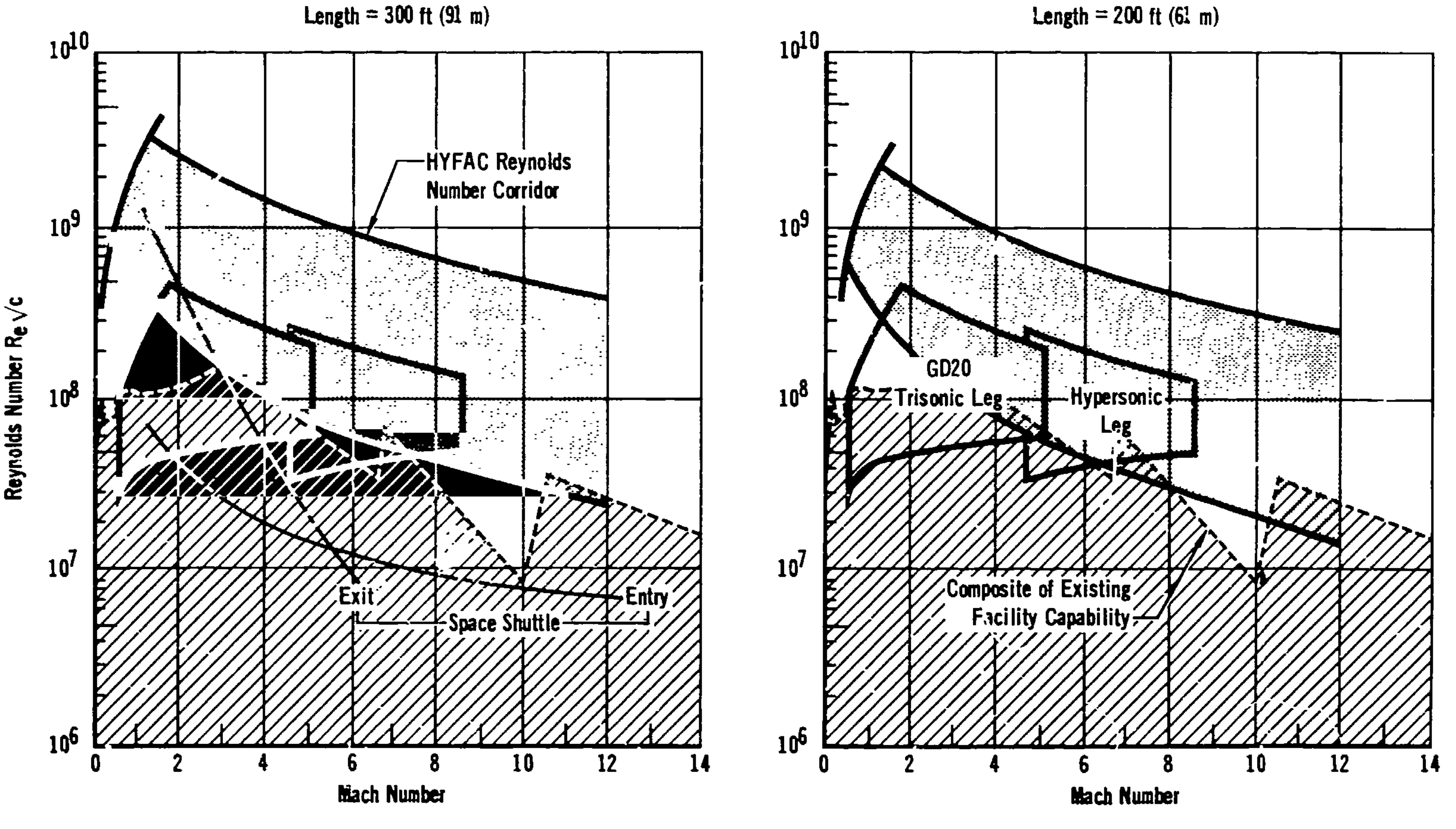
During Phase III, a final list of 278 Research Tasks, each task being a subset of the 78 Research Objectives, was defined. This list of research tasks was used to determine the research potential of each candidate research facility considered during Phase III.

Details of this analysis and evaluation are contained in Volume IV, Part 3, and are summarized below.

GD20 was identified with having contributions to more Research Objectives than any other single ground research facility, indicative of its versatility and capability. GD20 was evaluated as providing about 50% increase in research capability over existing facilities. Considering the already demonstrated capability of existing facilities similar to GD20, this judgement reflects the need for high Reynolds number research capability in the transonic and supersonic flight regimes and the influence that problems in this flight regime can have on the design performance of even hypersonic aircraft. This facility, therefore, is very relevant to the research and development capability required for potential operational aircraft. GD20 has application not only to aircraft characteristic of the HYFAC study, but can provide a significant increase in research capability for tactical and strategic military systems, commercial transports and V/STOL aircraft. For example, a subsonic model with wing aspect ratios between 6 and 9 could be tested at Reynolds numbers (based on mean aerodynamic chord) from 27 to 18 million. This is about 2.5 times the present capability (Reference (2)).

The following matrix is representative of the capability of GD20.

FIGURE 4-12
ESTABLISHMENT OF REYNOLDS NUMBER SIMULATION CAPABILITY



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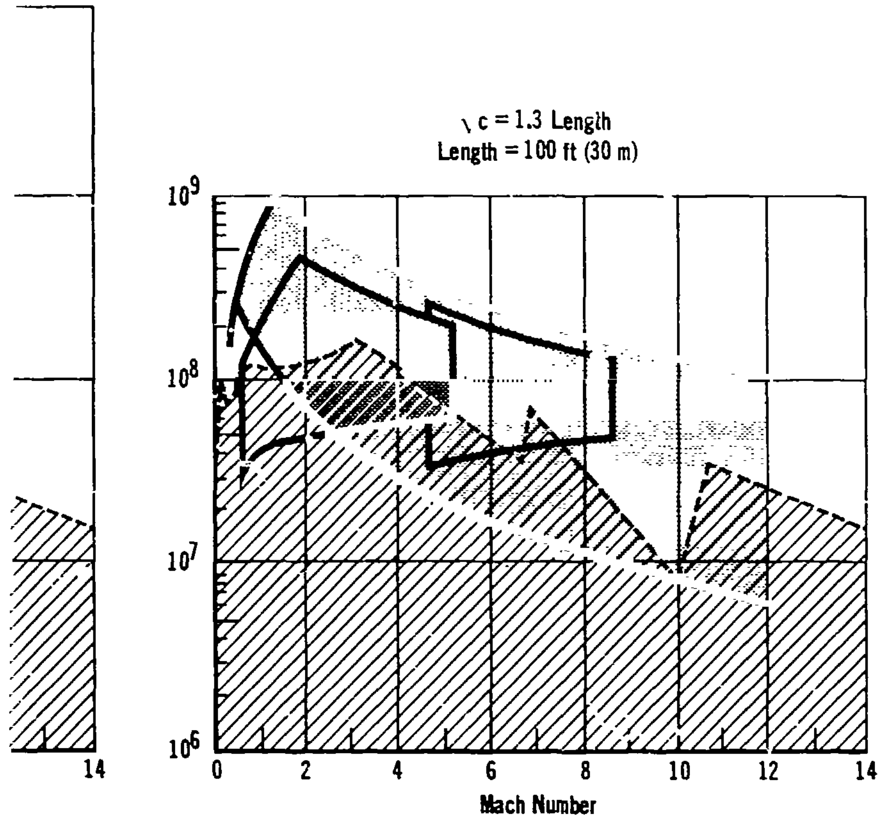

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Increased Research Capability in the Area of:	HYFAC	Large Subsonic Aircraft	Large Supersonic Aircraft	Tactical Aircraft	Strategic Aircraft	V/STOL Aircraft
Nozzle Thrust Minus Drag	●	●	●	●	●	●
Inlet Development	●	●	●	●	●	●
Compressibility Drag Rise	●	●	●	●	●	●
Shock Induced Separation	●	●	●	●	●	●
Aeroelastic Effects	●	●	●	●	●	●
Maneuvering Maximum Lift Coefficient	●			●	●	
Wall Interference	●	●	●	●	●	x
Ground Effects	●	●	●	●	●	x
Stability & Control	●	●	●	●	●	●
Power Effects	●	●	●	●	●	x

Contribution

● Significant

x Limited

Figure 4-13 summarizes the performance, costs, development assessment, and design characteristics of GD20. The numerical confidence level associated with the development assessment of GD20 is equal to 4.16. This numerical evaluation is consistent with a subjective evaluation that GD20 represents a larger version of equipment currently in operation, as based on the definitions in Section 2.4.

The low development risk associated with this facility implies that although large in size, it does not represent a major challenge to the current fabrication technology level, and that the major risk would probably be associated with the large, high pressure air storage system. Its operating principles have been demonstrated in many moderate sized, industry-owned wind tunnels. This particular facility can provide a significant increase in the research capability associated with large aircraft flying high dynamic pressure flight paths. As pointed out previously, the need for such Reynolds number capability is dominated by large air-breathing launch systems, transports, and military systems flying low altitude, acceleration flight paths. In order to have the necessary confidence to proceed with the development of such large vehicles, a facility having the capability of GD20 will probably be necessary.

FIGURE 4-13
PERFORMANCE AND FACILITY SPECIFICATIONS FOR GD 20

		Trisonic/ Test Leg	Hypersonic Test Leg
Test Section Dimensions	ft (m)	16 x 16 x 40 (4.9 x 4.9 x 12.2)	12 x 12 x 18 (3.7 x 3.7 x 5.5)
Mach Number		0.5 to 5.0	4.5 to 8.5
Stagnation Pressure	psia (N/cm^2)	17 to 294 (11 to 196)	150 to 2360 (103 to 1630)
Stagnation Temperature	°F (°C)	100 to 250 (37.8 to 121)	150 to 800 (65.5 to 427)
Minimum Run Time	sec	10.0	10.0
Time Between Runs Hr.	Avg. Max.	1 2	1 2

Cost – $145,943,000 Constructed on New Site
131,661,000 Integrated Into 16S/16T Complex at AEDC.

Confidence Level Assessment - 4.16 on a Scale from 1 to 5, where 5 Represents Low Risk Existing Equipment Technology, and 1 Represents High Risk Theoretically Predicted Technology.

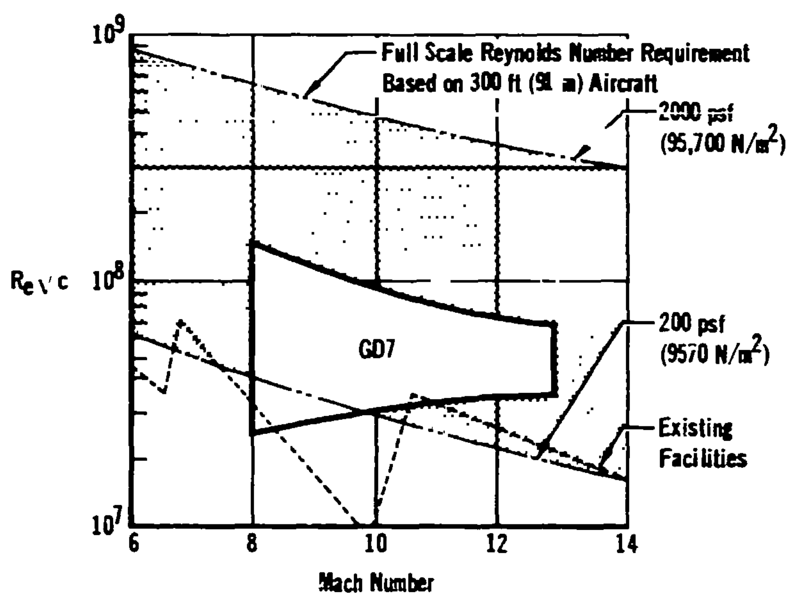
5. HYPERSONIC IMPULSE GASDYNAMIC RESEARCH FACILITY (GD7)

Extensive wind tunnel experimental research programs will provide the technology base from which development of an operational hypersonic aircraft can proceed. Although existing wind tunnel facilities will play a major role in developing this technology base, they cannot effectively simulate maximum Reynolds number conditions. This new facility will provide the additional capability in the Mach number region which is critical to the determination of hypersonic cruise range, fuel consumption, and maneuverability.

GD7 is a gas piston impulse tunnel which operates between Mach 8 and Mach 13, using nitrogen as the test gas. It consists of two independent test legs (Figure 5-1). Both legs have identically sized test sections, 10 feet in diameter (3.05 m), and have identical hardware downstream from the nozzle exit. One leg operates at Mach 8 through Mach 10, the other at Mach 10 through Mach 13.

In Phase II, size and pressure tradeoffs were made to determine their effect on facility component specifications and costs. It was found that the baseline facility definition, which is the smallest facility size able to produce the desired Reynolds number (one-fifth of the maximum full-scale values of the HYFAC operational vehicles), provided a significant increase in research capability as well as having the best research return per invested dollar. The baseline definition was therefore chosen to be carried forward into Phase III essentially unchanged in its capabilities.

The performance envelope for GD7, in terms of its Reynolds number simulation capability, is shown below. The Reynolds number capability is based on providing one-fifth the flight Reynolds number for a 300 foot (91 meter) long aircraft flying a 2000 psf (95700 N/m^2) dynamic pressure flight path. For smaller vehicles, and lesser dynamic pressures, the Reynolds numbers that GD7 provides are greater than a 20% Reynolds number simulation level.



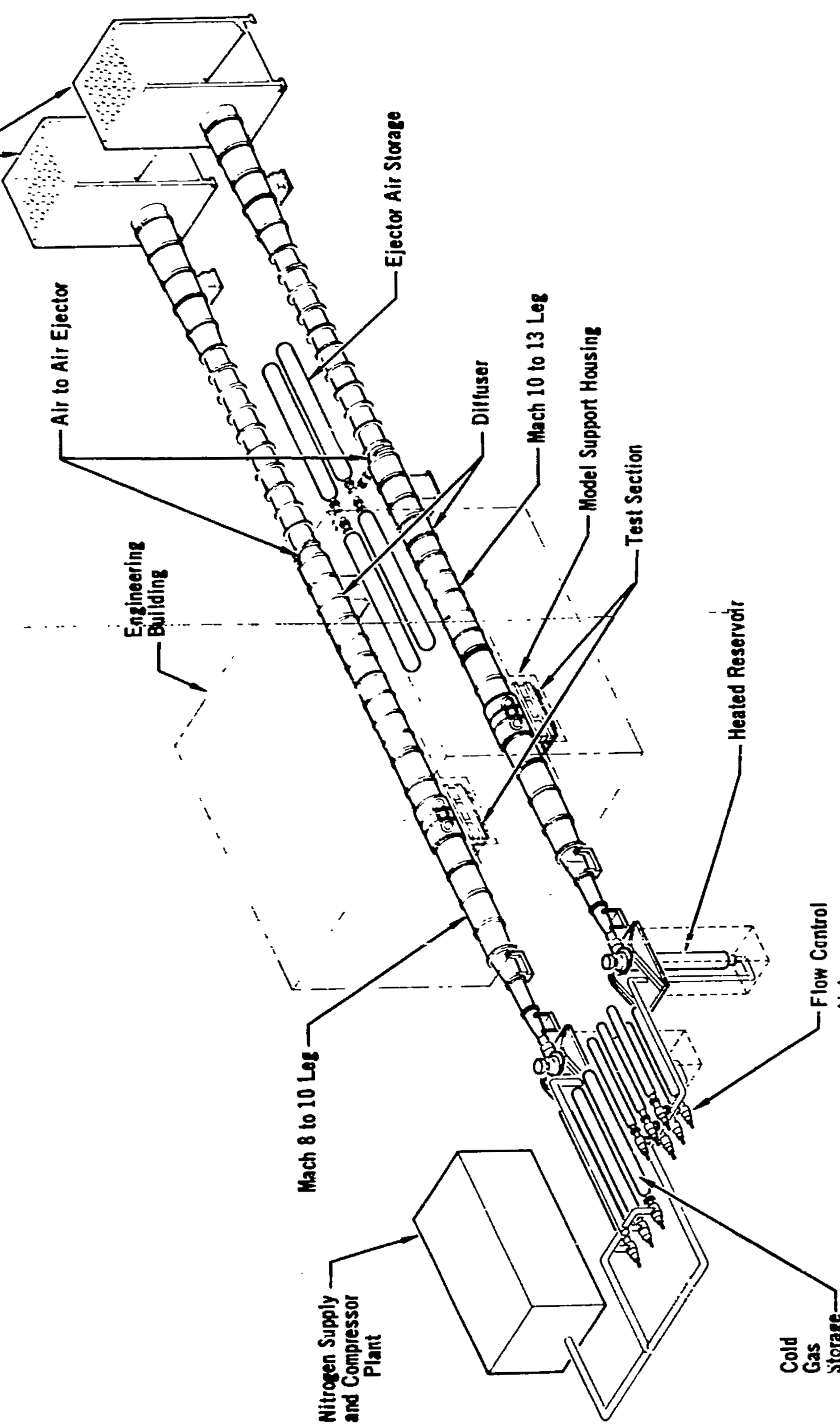


FIGURE 5–1
PHYSICAL PLANT GENERAL ARRANGEMENT – GD7

The shaded area represents the HYFAC potential operational hypersonic aircraft flight envelope, for a 300 ft (91 meter) long aircraft. The broken line represents the maximum capability for a composite of existing facilities. The reference length on which the Reynolds number is based is the square root of the wind tunnel test section cross sectional area, defined in Phase I as being equal to 1.3 times the aircraft or model length. This sizing criteria was selected because it provides a working tolerance to increase the operational flexibility of the gasdynamic facilities. A model sized for this facility would be about 7.1 feet (2.2 meters) long.

The gas piston impulse driver uses a technique developed at the Naval Ordnance Laboratory (NOL), whereby cold gas at the reservoir pressure is admitted to the upstream end of a heated reservoir. The cold gas acts as a gas piston to maintain reservoir pressure and expel most of the heated gas. These features eliminate the non-constant reservoir conditions associated with most fixed-volume reservoir impulse facilities. Comparison with available techniques shows that longer run times will be obtained from the gas piston technique.

Energy Source	Run Time	Remarks
Shock Tube	1 millisecond	Turbulent boundary layer limited run time
Arc Chamber (Hotshot)	70 millisecond	Pressure/temperature decays with time, quasi-steady state
Gas Piston	2 second	Limited by length of heated reservoir

This facility is larger than existing and proposed wind tunnels of its type, but is, in fact, an extension of existing equipment and therefore does not necessarily require advances in technology. The fact that the facility is quite large does not in itself imply that higher than normal development risks will be encountered.

The following sections describe the work done to refine the facility design and performance, the results of this refinement in terms of facility descriptions and costs, considerations of safety and site criteria, an assessment of the critical areas in developing the facility, and an analysis of the total facility acquisition schedule.

5.1 REFINEMENTS IN DESIGN AND PERFORMANCE

All work done in Phase III on this facility was concentrated on improvement of the design and specifications of the test legs and facility systems. The major goal was to refine the specifications so that the facility will meet its performance definition at a reasonable acquisition and operating cost. No performance compromises or redefinitions have been made.

The following tasks were performed in order to attain the goal of improved facility description and minimized costs:

(1) Structural and mechanical layout of both test legs was done by Fluidyne Engineering Corporation, using the Phase II facility sketches as a starting point. Their experience in facility design was useful in searching out and solving problem areas and in obtaining a good, detailed facility description. Test leg cost estimates were done using the Fluidyne drawings as a basis.

(2) Review of mechanical and fluid dynamic principles of the gas piston driver with personnel at NOL to reflect latest concepts. This resulted in specific hardware design details and sizing criteria. These criteria, in terms of minimum Froude number in the hot gas section of the gas piston driver, resulted in the new requirement for two heaters, and thus two separate test legs to cover the total facility Mach number range. Prior to this analysis it was thought that one heater and test leg would be sufficient.

(3) Review of different methods to provide energy to the heated reservoir. The graphite rod heater currently employed by NOL has been tentatively selected although several methods should be considered as part of a formal design study.

(4) Identification of safety hazards, procedures, interlock, and special system needed to operate the facility safely. The most hazardous area of the facility is the liquid nitrogen gasifier and compressor system and the gas piston drivers which operate at extremely high pressures. The test legs themselves offer no unusual hazards with the possible exception of the very high impulsive noise level during a run.

(5) The facility was analyzed for construction problems and an acquisition schedule, up to and including facility shakedown and calibration, was developed. The major design and constructional difficulty is found in the high pressure, heated gas piston driver vessels and control valves.

(6) The facility was analyzed with respect to site selection criteria. In this case it appears that any existing wind tunnel facility complex could be an appropriate site, such as NASA Langley, NASA Ames, AEDC, or NOL.

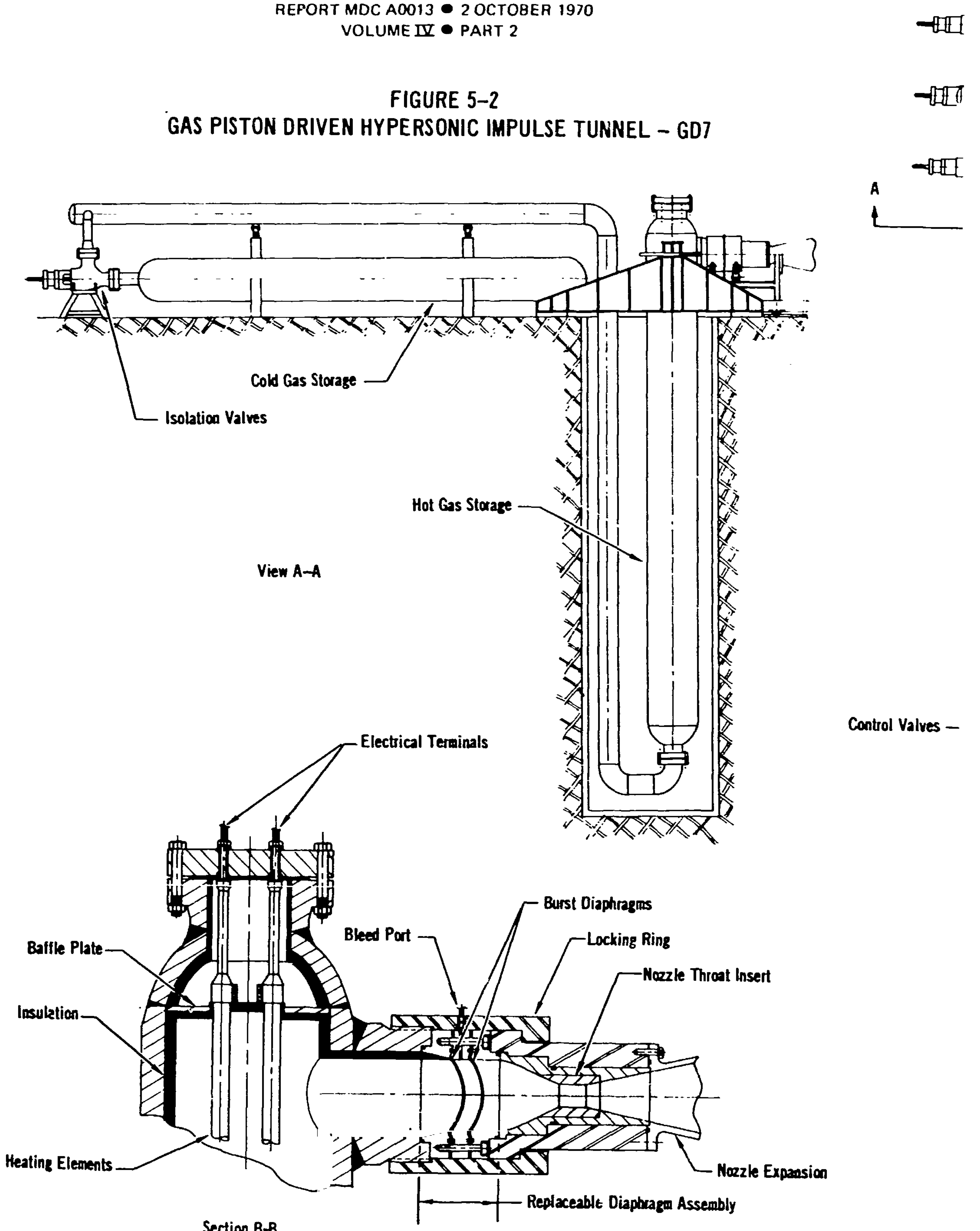
(7) The development risks, and acquisition and operational problems were evaluated for each major component, then compiled into an overall facility confidence level rating. The major problem areas associated with the major components and overall facility were identified.

(8) The facility was evaluated in terms of its ability to satisfy the performance goals specified originally in Phase I as necessary to accomplish the Research Objectives appropriate to GD7.

5.2 FACILITY DESCRIPTIONS AND COSTS

The overall facility plant concept is shown in Figure 5-1, with the details of the test legs shown in Figure 5-2. As indicated in the plant layout, although the facility is quite large, the basic plan is simple in concept, using only a minimum of ancillary systems to provide facility operation.

FIGURE 5-2
GAS PISTON DRIVEN HYPERSONIC IMPULSE TUNNEL – GD7



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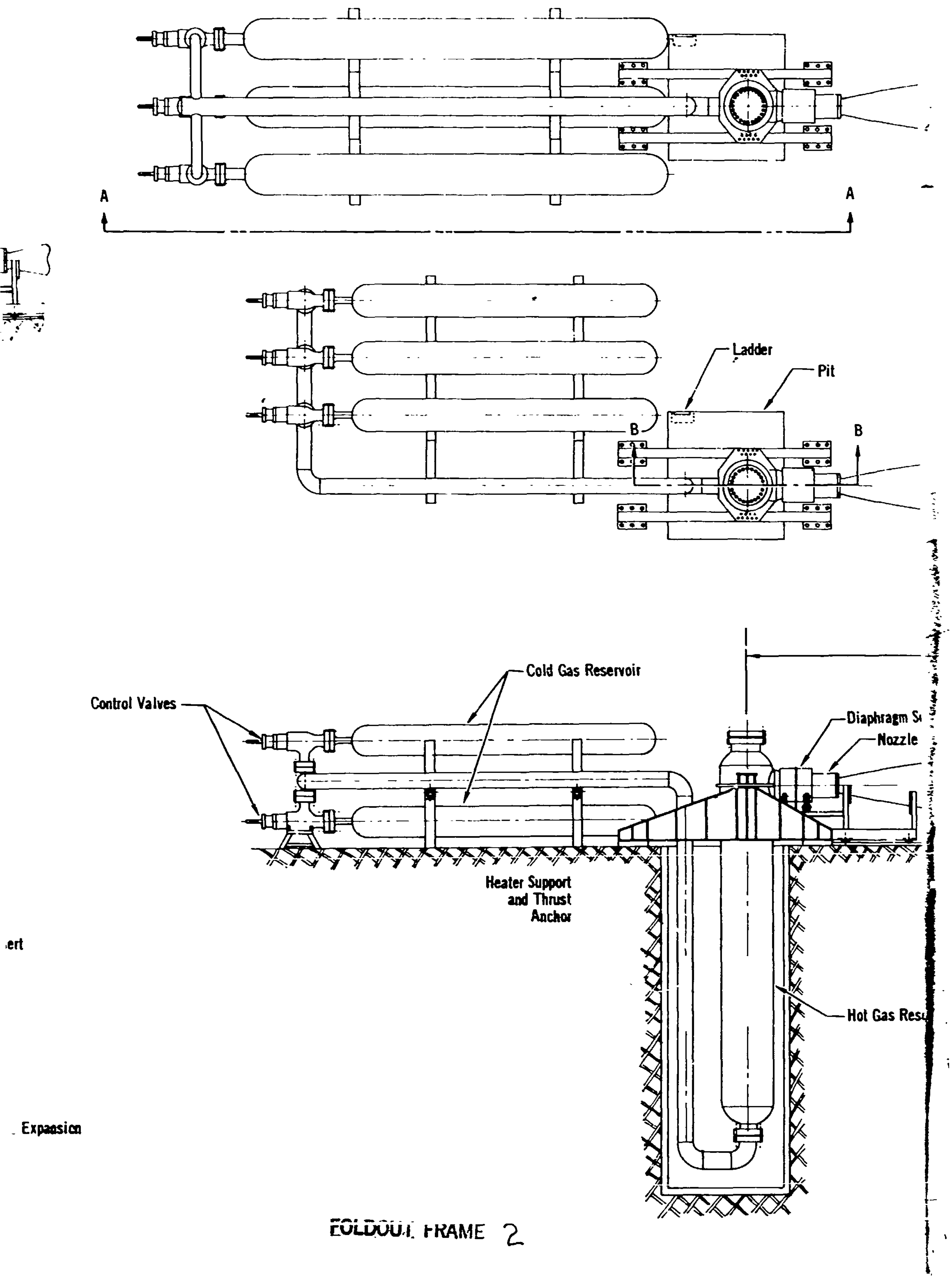
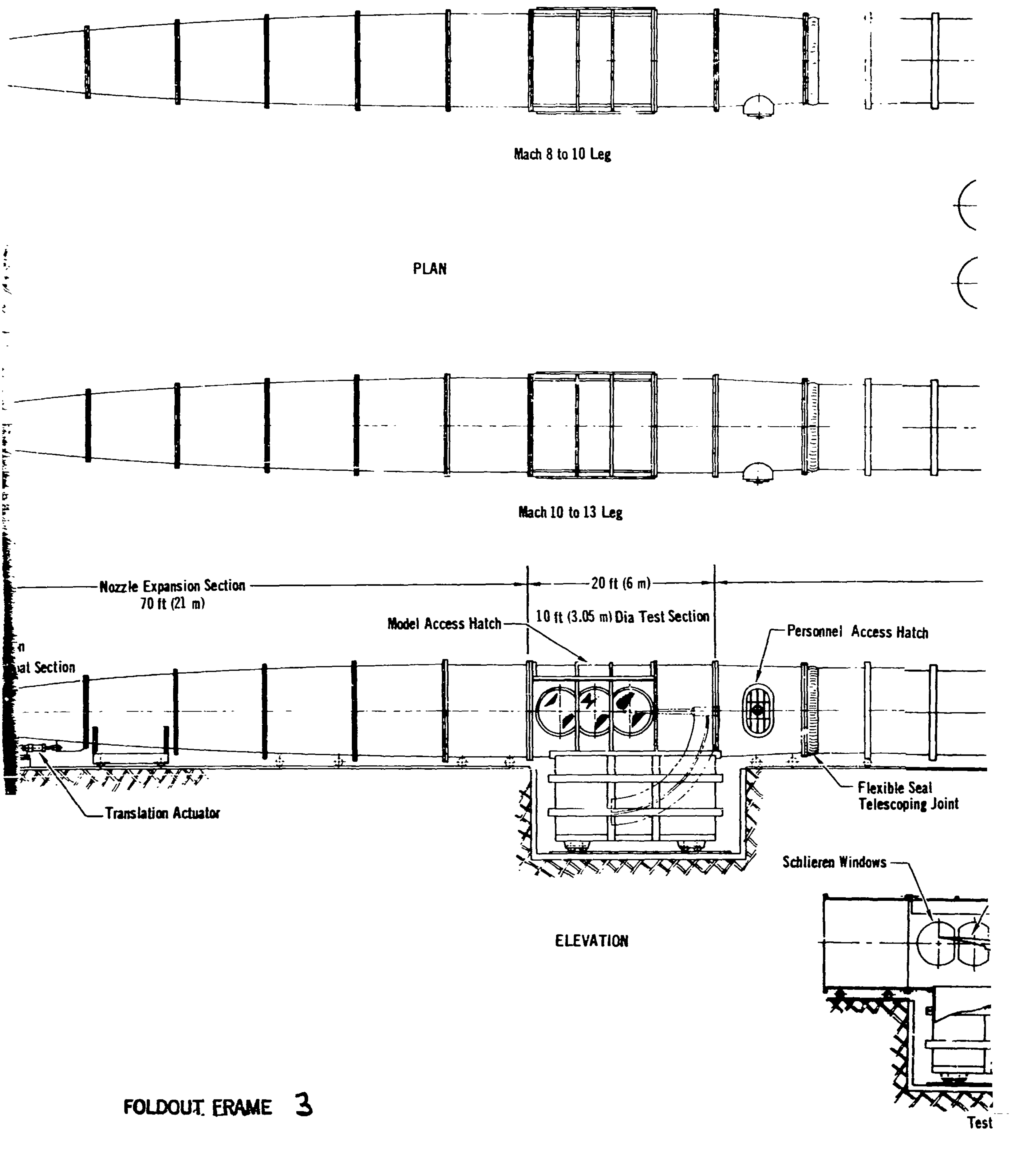


A
A
Ladder
Pit
B
B
Cold Gas Reservoir
Control Valves
Nozzle
Heater Support
and Thrust
Anchor



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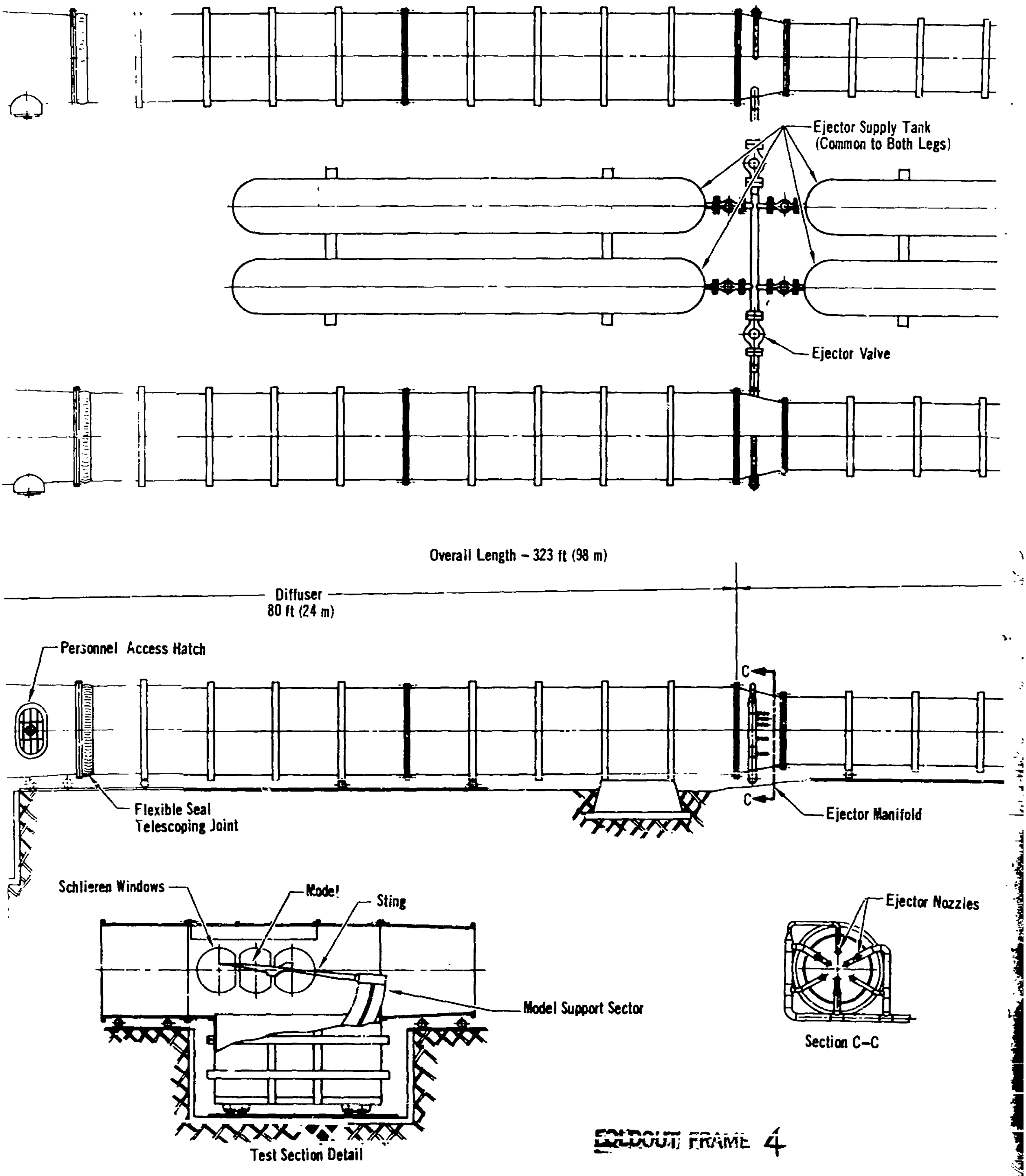

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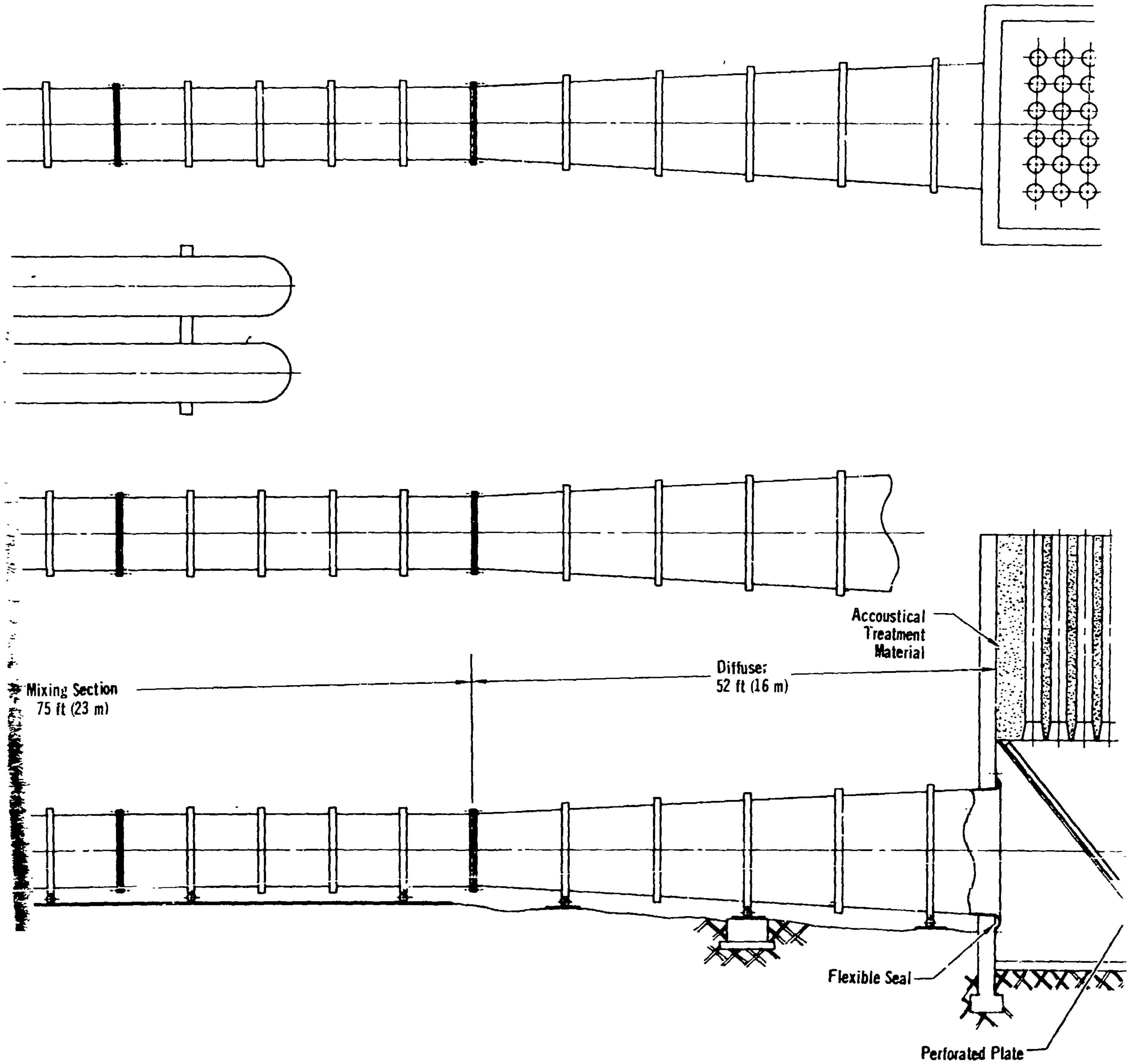

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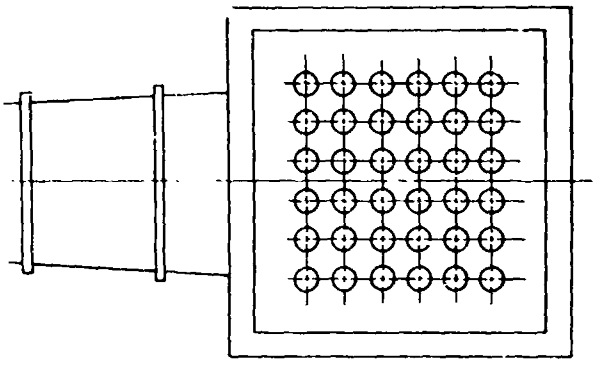
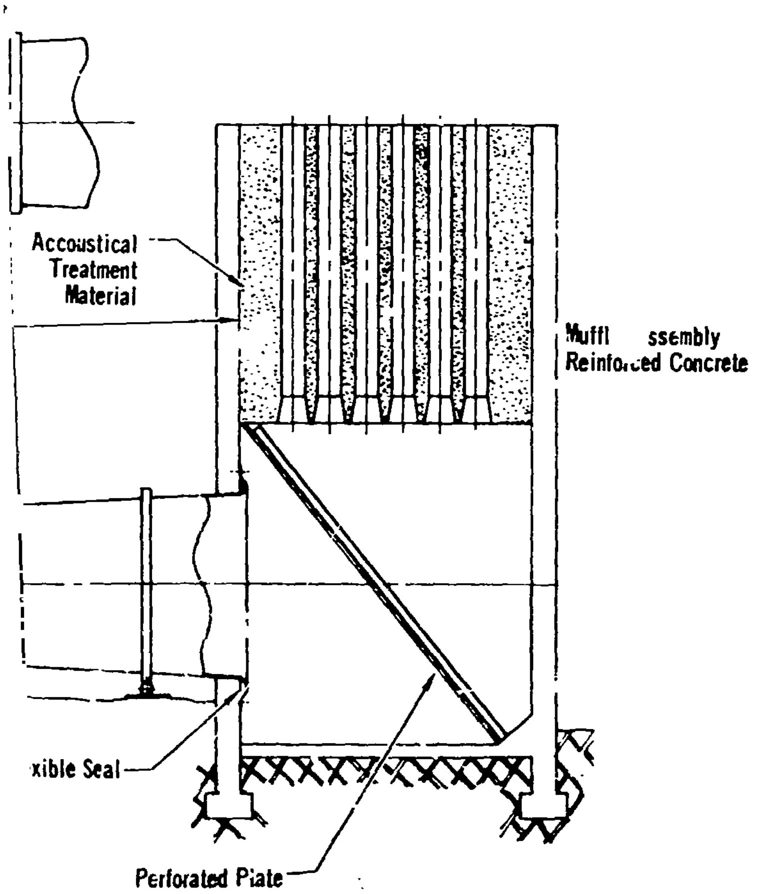




Accoustical
Treatment
Material
Muffl ssembly
Reinfo.ced Concrete
xible Seal
Perforated Plate

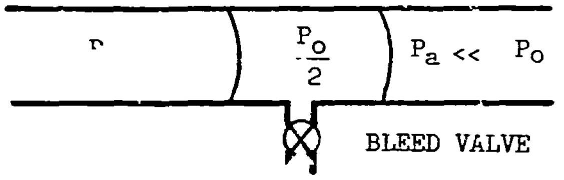
The Hypersonic Impulse Gasdynamic Research Facility can be subdivided into a number of components to facilitate the discussion of the component description, cost, and development assessment. The order of discussion is the test legs, the gas piston drivers, and the nitrogen liquid/gas converter system.

5.2.1 TEST LEGS - The test legs are basically larger versions of existing wind tunnels. They incorporate numerous concepts from several facilities to enhance their usefulness and flow quality. The details of the test legs are shown in Figure 5-2. The basic test leg consists of an axisymmetric contoured nozzle designed for its highest operating Mach number. Uncooled replaceable throats are used to vary the Mach number of the fixed contour nozzle. A fixed throat diffuser provides the means of recovering some of the stream kinetic energy. An air ejector pump with a pressure ratio of 2 ensures that the facility can be successfully operated with diffuser recovery pressures as low as 7 psia (4.8 N/cm^2).

An upstream anchor at the intersection of the heater vertical centerline and the test leg centerline takes out the nozzle thrust loads. The heater is allowed to move downward to take care of thermal expansion. The nozzle and test section are supported on rollers which allow thermal expansion. The diffuser section is anchored in its middle and is supported along its length by rollers on rails. An expansion joint connects the test section to the upstream end of the diffuser. A second expansion joint is provided where the downstream end of the diffuser enters the muffler.

The nozzle throat section connects the heated gas reservoir to the nozzle. This section incorporates a threaded nut with an external chain drive which is unscrewed for access to the throat and diaphragms. The nut rides on a roller cradle which allows rearward motion of the nut with respect to the nozzle. Having loosened the nut, the entire nozzle and test section translates rearward a short distance to provide working room in the throat section. Inspection and replacement of the nozzle throat section and diaphragm package are accomplished while model adjustments and changes are being made in the test section.

The diaphragm package, which is changed for every run, is a stack of two or more burst diaphragms with known burst pressures. This system is used to provide run initiation at exactly the correct stagnation pressure and to provide a starting signal for the data acquisition system and the throttling valves (see Sec. 5.2.2). The operating principle of the multiple diaphragms is quite simple, as illustrated for a two diaphragm system:



Each diaphragm seals against approximately half the charge pressure. When the run set-point stagnation pressure has been achieved in the hot gas reservoir and run initiation is desired, the bleed line is opened, reducing the pressure in the intermediate volume between the two diaphragms. The upstream diaphragm becomes overstressed and ruptures, thus causing the downstream diaphragm to rupture.

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The nozzle throat insert is inspected and changed, if necessary, at the same time that the diaphragm package is installed. The throat insert is a small section with a conical entrance and exit and a cylindrical throat with an L/D = 1.0. Variations in test Mach number are obtained by using different throat diameters.

The axisymmetric nozzle of each test leg is 10 ft (3.05 m) in diameter at the test section and 70 ft (21.3 m) long. Each nozzle consists of seven conical sections with precision machined interior contours. The exact matching of the contours of adjacent sections with no steps or slope changes is the only constructional problem foreseen with these relatively simple test legs.

A closed jet test section is provided, which incorporates an overhead model access hatch, a personnel access hatch, large schlieren windows and a model support system.

The model support concept is one which provides a variable pitch capability during a run, so that a 20° to 25° angle of attack sweep can be made during one run. Based on data from MCAIR and ONERA (L'Office National D'Etudes et de Recherches Aerospatiales, 92-Chatillon, Bagneux, France), pitching rates up to 200 degrees per second are possible without introducing significant unsteady aerodynamic effects with flow velocities on the order of 7000 ft/sec (2140 m/sec) and model lengths of 2 ft (.61 meters). Based on a model length of 6.8 ft (2.1 m) and a minimum velocity of 4000 fps (1220 m/sec) in GD7, the same guideline permits pitching rates up to 34°/sec, sufficient to complete a pitch polar during even the shortest run time available.

An air to air ejector system is installed downsteam of the diffuser to increase the starting pressure ratio and permit operating at static pressures less than one atmosphere. Starting loads are reduced because of lower starting dynamic pressures and shorter flow establishment times. Six ejector nozzles, operating at constant primary flow stagnation pressure, are used, in conjunction with a long (L/D = 10) constant diameter mixing section, which permits efficient operation throughout a wide range of facility mass flows.

A tank farm, consisting of 3900 ft^3 (110 m^3) of storage volume at a pressure of 1100 psi (760 N/cm^2), provides primary air to each of the test leg ejector systems. A single automatically controlled valve upsteam of each ejector manifold regulates the ejector stagnation pressure. These control valves must be interlocked to prevent operation except when the facility is ready for a run.

A muffler is provided on each test leg to silence the exhaust noise. A perforated plate at the entrance to the muffler attenuates the low frequencies and tube type exhaust stacks lined with acoustical damping material are used to attenuate high frequencies. The muffler is built of reinforced concrete and is patterned after a design which has successfully met the noise attenuation requirements specified for the city of El Segundo, California (see Appendix A).

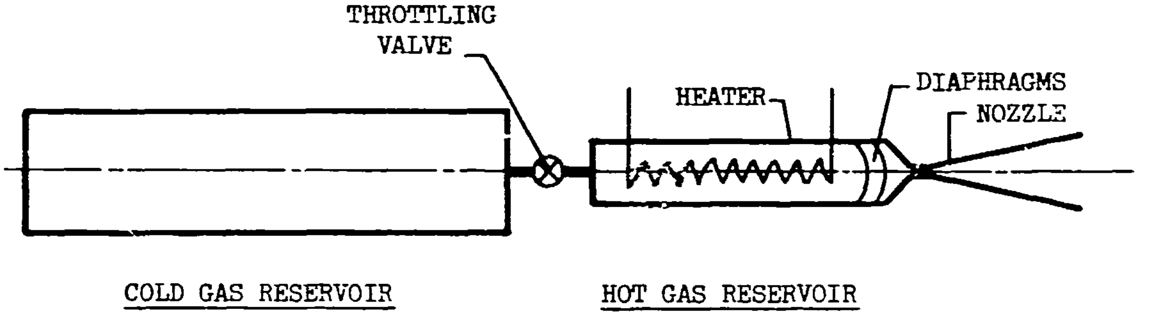
The chief safety hazard to personnel in the test legs exists when the cold and hot sections of the gas piston driver are charged with high pressure nitrogen prior to a run. The diaphragms are the only seal between the gas piston driver and the test section. Therefore, mechanical and electrical interlocks must be provided which prevent charging of the gas piston driver sections, or opening of the ejector control valves while any access hatches to the test section or muffler are open, or while the nozzle is translated for throat inspection and diaphragm replacement. A panic button should be provided at various stations in the test leg to disable the charging and valve control circuits in case personnel are working with the doors or hatches closed. In addition, interlocks should be provided to prevent access to the test leg once the gas piston driver has been charged.

The cost of both test legs is estimated to be $2,002,000, including the ejector tank system. A breakdown of the cost estimates is given in Section 5.2.4.

The model support, with its severe pitch rate requirements and large size, has a confidence level of 3, while the remainder of the test leg components have a confidence level of 5. The composite confidence level rating of the test legs is 4.5.

5.2.2 GAS PISTON DRIVER - The gas piston driver concept was probably first employed by Victor Zakkay at New York University. It has been further refined at NOL, where a facility with three test legs, operating at pressures as high as 60,000 psia (34,000 N/cm²), and at Mach numbers up to 20, is under construction.

The principle of operation is as follows. Two gas reservoirs are provided, separated by a throttling valve, and sealed from the test leg by a diaphragm system (see Section 5.2.1).



Once servicing of the throat section and diaphragm replacement is completed, the hot gas reservoir is charged to a designated pressure less than the run P_o and sealed. The cold gas volume is charged to a pressure higher than the set point run stagnation pressure. The heaters are then turned on until the desired pressure and temperature is reached. Since the reservoir has constant volume, the pressure and temperature will rise as thermal energy is added. When the desired stagnation pressure and temperature are established in the hot gas reservoir, the facility run is started by breaking the diaphragms separating the hot gas reservoir from the aerodynamic nozzle. The signal which initiates diaphragm rupture also initiates opening of the throttling valve separating the cold and hot gas reservoirs. As the hot gas flows out of the hot gas reservoir into the nozzle, cold gas is admitted at a constant pressure equal to the run set-point Po, thus permitting constant pressure testing for the duration of the run. The cold air, admitted to the hot gas section at constant pressure, acts like a piston, driving the hot gas out, thus the name <u>gas piston driver</u>. This piston action is the key to the operation of the facility and is the mechanism by which relatively long run times can be attained in an impulse type facility.

In order to maintain a constant pressure downstream of the throttling valve, the valve must open progressively, since the upstream pressure in the cold gas reservoir is decreasing rapidly (a polytropic expansion with n = 1.4). The throttle valve opening must be electronically or mechanically programmed to provide a constant downstream pressure. Control of the throttle valve is a development problem that must be solved experimentally.

The facility run is terminated when the cold/hot gas interface reaches the nozzle throat. At that time, the gas pressure in the cold section must be at least equal to the run Po plus valve pressure drop. It is this consideration that establishes the minimum initial cold gas reservoir charge pressure.

The following sections discuss the components of the gas piston driver and some of their design considerations.

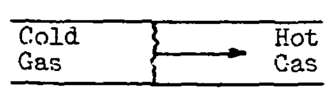
<u>Hot Gas Reservoir</u> - The key to successful operation of the gas piston driver is maintaining a thin, plane interface between the cold and hot gas by providing sufficient interface speed, such that, in a horizontal reservoir, the cold gas does not undercut the hot gas. NOL has experimentally determined that for Froude numbers greater than 12, the interface speed is sufficient to prevent serious undercutting.

$$F_r = \sqrt{\frac{V^2}{Dg}} \geq 12$$

$F_r < 12$

where V = velocity of interface
D = diameter of reservoir
g = acceleration of gravity

$F_r > 12$



The heaters depicted in Figure 5-2 are shown vertical to minimize thermal convection effects. However, the design is such that they can operate horizontally, if necessary, by conforming to the above rule.

At first, one heater serving the entire Mach number range was considered. However, there is a large difference in mass flow and pressure required for the Mach 8 and Mach 13 test conditions. A very large hot gas section was required to satisfy the mass flow for Mach 8. Sizing this section for reasonable cold/hot gas interface velocities resulted in interface velocities too low to satisfy the Froude number criterion when operating at Mach 13 (low mass flows). In addition, the hot gas section had to be stressed to the very high pressures associated with high Mach number operation. The configuration required would have had a volume of 345 ft^3 (12.3 m^3), an internal diameter of 42.5 in (108 cm) and would be stressed to hold the 18,800 psia (13,000 N/cm^2) needed for Mach 13 operation.

It was decided to obtain a more rational hot gas reservoir design by splitting the total Mach number range in half and designing separate heaters for each range. With two heaters required, there are three facility arrangements possible.

- Single test leg, fixed, with 2 heaters which can be installed alternately.
- 2 heaters fixed in position, with a single test leg which translates laterally for installation.
- 2 heaters and 2 test legs, both fixed.

It was decided to use the last arrangement because of the size and weight of both heater and test leg and the requirement that both be firmly anchored.

Many types of heating could be used to add thermal energy of the gas in the hot gas reservoir. These are discussed in Volume III, Part 1, but are summarized here:

- Resistance heater
- Arc heater (hot shot principle)
- Induction heater
- High pressure arc heater (HEAT concept of W. Boatwright of NASA Langley).

Each of these has particular advantages, and a formal design study of the gas piston heater as applied to this Mach range should include consideration of these heating methods. For the purpose of this study, a resistance heater of the graphite rod type was assumed, this concept being in current operation at NOL, and representing a minimum risk concept on which to base costs.

Graphite heating elements are required to handle the 2500°R (1390°K) stagnation temperature needed for Mach 13. Selection of graphite requires the use of nitrogen as the test gas and thus incurs the additional expense of purchasing nitrogen and of providing a nitrogen liquid/gas converter system (described in Section 5.3.3). It is possible to use a heater element compatible with air for the low Mach number heater, but a graphite heater is described now for simplicity.

	Mach 8-10	Mach 10-13
Hot Gas Reservoir Volume	435 ft^3 (123 m^3)	173 ft^3 (4.9 m^3)
Length	44.2 ft (13.5 m)	32.6 ft (9.9 m)
Inside Diameter	3.54 ft (1.1 m)	2.6 ft (.79 m)
Maximum Pressure	6700 psia (4620 N/cm^2)	18,800 psia (13,000 N/cm^2)
Maximum Temperature	1700°R (945°K)	2500°R (1390°K)
Heater Max. Power	8.4 megawatts	

(Based on 4 minute heating cycle, 70% efficient)

COLD GAS RESERVOIR - Each test leg is also provided with a separate cold gas reservoir, consisting of a rack of pressure vessels. Their specifications are:

	Mach 8-10	Mach 10-13
Total Volume	1180 ft^3 (33.4 m^3)	700 ft^3 (19.8 m^3)
Maximum Pressure	8560 psia (5900 N/cm^2)	24,000 psia (16,600 N/cm^2)
Number of Vessels	3	6
Vessel Length	44.1 ft (13.4 m)	30.8 ft (9.4 m)
Vessel Inside Diameter	3.33 ft (1.02 m)	1.67 ft (.505 m)

THROTTLING VALVES - Each bank of cold gas pressure vessels is manifolded to a single pipe which serves as the inlet to the hot gas reservoir. A single valve isolates each cold gas vessel from the common line and serves as the throttling valve. Multiple valves are used for the same reasons that multiple blowdown valves are used on GD20, i.e., improved control of downstream pressure over a wide range of mass flow. Particularly important for GD7 is the desirability of reducing valve size to a minimum when pressures are so high. As it is, a development program will be necessary to design the large, high pressure throttling valves and the fast response valve control and actuator system.

The cost of the two gas piston drivers is estimated to be $10,758,000 and the confidence level is 3.8.

5.2.3 NITROGEN LIQUID/GAS CONVERTER SYSTEM - The gas supply uses a liquid nitrogen storage system with a steam heated vaporizer and high pressure compressors. A high pressure charging line connects the system to each of the gas piston drivers. To charge the gas piston drivers, the facility must be in a run configuration, with diaphragms installed and the inter-diaphragm pressures set, the nozzle connected to the driver, and all access doors shut. This combination of conditions will allow the actuation of the charging circuits. At the start of charging, the throttle valves between the hot and cold gas sections are open. When the pressure reaches the proper charge level for the hot gas section (considerably less than run P_O), the throttling valves are closed, and the cold gas reservoirs continue to be charged, until they reach their prerun condition. The gas piston driver is then isolated and ready for a run. The liquid gas converter system is then de-energized and depressurized.

This system is comprised entirely of commercial equipment and is obtained as a package installation. The description of the system is:

Liquid Storage Volume	13,000 gal. (49 m^3)
Vaporizer - Steam Heated	
High Pressure Compressors	25,000 psi (17,200 N/cm^2)
Piping, Valving, & Controls	
Total Installed Power	1,400 hp (1040 kW)

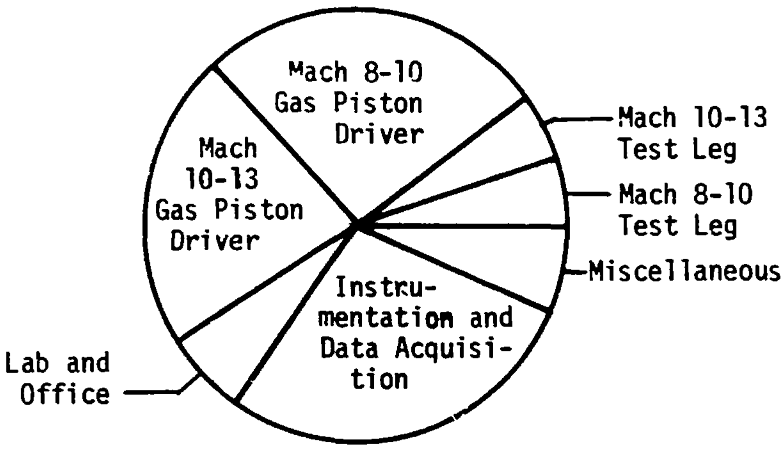
The liquid/gas converter system is estimated to cost $468,000 and has a confidence level of 5.

5.2.4 <u>COST SUMMARY</u> - Figure 5-4 presents a detailed cost breakdown for the GD7 facility, based on the costing techniques presented in Section 2.

The contributions of the components to the total cost are shown in Figure 5-3 . The relative cost of this facility as compared to the other ground test facilities is expressed by the relative areas of their respective pie charts. GD7 is, of course, the least expensive facility in the study, a result to be expected as a consequence of its impulse mode of operation.

FIGURE 5-3
DISTRIBUTION OF FACILITY ACQUISITION COSTS – GD7

Total Acquisition Cost: $24,187,000



The distribution of costs among the facility components has changed from Phase II to Phase III as a result of more detailed calculations of component requirements and costs. As indicated in the pie charts, whereas Phase II showed that the test leg represented a major portion of the overall costs, the Phase III results show that instrumentation and the gas piston drivers now represent the major cost items.

The operating costs of GD7 were estimated based on the ground rules presented in Section 2.3.2, using the following assumptions:

U_p = Power Utilization Factor	= .3	for Graphite Resistance Heater
	= 1.0	for N_2 Compressor
	= 1.0	for Ejector System Compressor
t_i = Time Used Per Run	= .067	hr for Electric Heater
	= 2.0	hr for N_2 Compressor
	= 2.0	hr for Ejector Compressor

Average Runs/Occupancy Hour = .25, allowing for Test Installation and Removal.

N_s = Staff Directly Charging to Facility = 50

Annual Maintenance Budget = $30,000

FIGURE 5-4
COST SUMMARY - GD7

Facility Component	Cost ($1000's)
Test Leg, Mach 8 to 10	
Footings and foundations	70
Fixed contour nozzle	165
Test cabin including schlieren windows	464
Model support system	150
Mixer section	84
Ejector	18
Fixed diffuser section	71
Muffler	102
Subtotal Test Leg, Mach 8 to 10	1,124
Test Leg, Mach 10 to 13	
Footings and foundations	70
Fixed contour nozzle	165
Test cabin including schlieren windows	464
Model support system	150
Mixer section	84
Ejector	18
Fixed diffuser section	71
Muffler	102
Subtotal Test Leg, Mach 10 to 13	1,124
Gas Piston Driver, Mach 8 to 10 Test Leg	
Hot gas reservoir	2,540
Graphite resistance heater	279
Cold gas reservoir storage tanks	2,412
Piping (to test leg)	277
Throttling valves	380
Subtotal Gas Piston Driver, Mach 8 to 10 Leg	5,888
Gas Piston Driver, Mach 10 to 13 Test Leg	
Hot gas reservoir	1,390
Graphite resistance heater	202
Cold gas reservoir storage tanks	2,759
Piping (to test leg)	139
Throttling valves	380
Subtotal Gas Piston Driver, Mach 10 to 13 Leg	4,870
Air Ejector Tank System	
Storage Tanks	317
Piping (to ejector air storage)	7
Compressor (air)	90
Subtotal Air Ejector Tank System	414

FIGURE 5-4 (Continued)
COST SUMMARY - GD7

Facility Component	Cost ($1000's)
Nitrogen Liquid/Gas Converter System	
Liquid nitrogen storage, vaporizer, compressor	330
Piping (to nitrogen storage)	138
Subtotal N_2 Liquid/Gas Converter System	468
Laboratory and Office Building	1,400
Substation	300
Automatic Control System	
Mach 8 to 10 Leg	100
Mach 10 to 13 Leg	100
Subtotal Automatic Control System	200
Instrumentation and Data Acquisition	
Mach 8 to 10 Leg	3,100
Mach 10 to 13 Leg	3,100
Subtotal Instrumentation and Data Acquisition	6,200
Total GD7 Components	21,988
Contingency @ 10%	2,199
Total GD7 Facility Cost	24,187
A & E Fee @ 6%	1,456
Management and Construction Coordination Fee @ 4%	963
Grand Total GD7	26,606

U_f = Facility Utilization Factor = .3

Using these factors results in the following breakdown of operating cost per tunnel occupancy hour.

Power	$ 10
Staff	1,670
Maintenance	50
Total	$1,730

5.3 SPECIFIC SITE CONSIDERATIONS

Owing to the relatively small size and low power requirements of GD7 there are no factors favoring its installation at any specific site. Practicality would dictate that this facility be located at an existing wind tunnel complex such as NASA Ames, NASA Langley or NOL.

5.4 DEVELOPMENT ASSESSMENT

The general rules for the development assessment are presented in Section 2.4. Individual component assessments are contained in each subsection discussion and are summarized here. The following figure lists the individual facility element, cost fraction, confidence level evaluation, and ranking of the technical risk.

GD7 Development Assessment Summary

Item	Cost Fraction (K_i)	Confidence Level (CL_i)	$K_i\ CL_i$	Percent Technical Risk	Technical Risk Ranking
Mach 8-10 Test Leg	.051	4.5	.229	4.67	4
Mach 10-13 Test Leg	.051	4.5	.229	4.67	4
Mach 8-10 Gas Piston Driver	.268	3.8	1.018	36.05	1
Mach 10-13 Gas Piston Driver	.220	3.8	.836	29.57	2
Air Ejector Tank System	.019	5.0	.095	1.16	8
N_2 Liquid/Gas Converter	.021	5.0	.105	1.28	7
Laboratory and Office	.064	5.0	.320	3.91	6
Substation	.014	5.0	.070	.86	9
Automatic Control System	.009	5.0	.045	.55	10
Inst. and Data Acquisition	.282	5.0	1.410	17.23	3
Total	1.000		4.36	100.00	

The numerical confidence level associated with the development assessment of GD7 is equal to 4.36. This numerical evaluation is consistent with a subjective evaluation that GD7 essentially represents a large version of existing impulse wind tunnels.

The low development risk associated with this facility implies that, although large in size, it does not represent a major challenge in design or fabrication. The highest risk items are the gas piston drivers, largely because of the very high pressures which must be contained, and because of the throttling valve development program which must be conducted. The operating principles of the test legs have been demonstrated in many existing impulse and blowdown wind tunnels while the operation of the gas piston driver has been proven at New York University and NOL. These applications, however, were for small tunnels of higher Mach number than GD7, so it cannot be said that the gas piston driver is a proven concept in this application. There is no reason to doubt that a successful gas piston driver can be developed, although a working design may differ appreciably in arrangement, detail, and even specific heater type as mentioned in Section 5.2.2. The numerical confidence level of 3.8 given to the gas piston drivers reflects these considerations.

In summary, GD7 is a large version of existing hypersonic tunnel design concepts with a very high confidence level with respect to its successful design, fabrication, and performance.

5.5 ACQUISITION SCHEDULE & TIMING

The schedule for acquisition of GD7 is presented in Figure 5-5 and is based on the general considerations given in Section 2.8. It is seen that the facility can be available for use in slightly less than 5 years.

The 4-2/3 year acquisition schedule is reasonable for a facility of the size and capability of GD7. Some time elements could be reduced if the program were conducted on a crash basis, but the proposed schedule is conservative and allowance has been made for the usual slippage on a major facility effort. The total period of 8 months from completion of construction to the end of initial calibration embraces facility demonstration tests as well as calibrations and may be longer than would be allowed under the pressure of test program schedule demands. Still, this time should be spent before routine test programs are scheduled. The cost and schedule for acquisition of the complete facility are then:

Cost $26,606,000

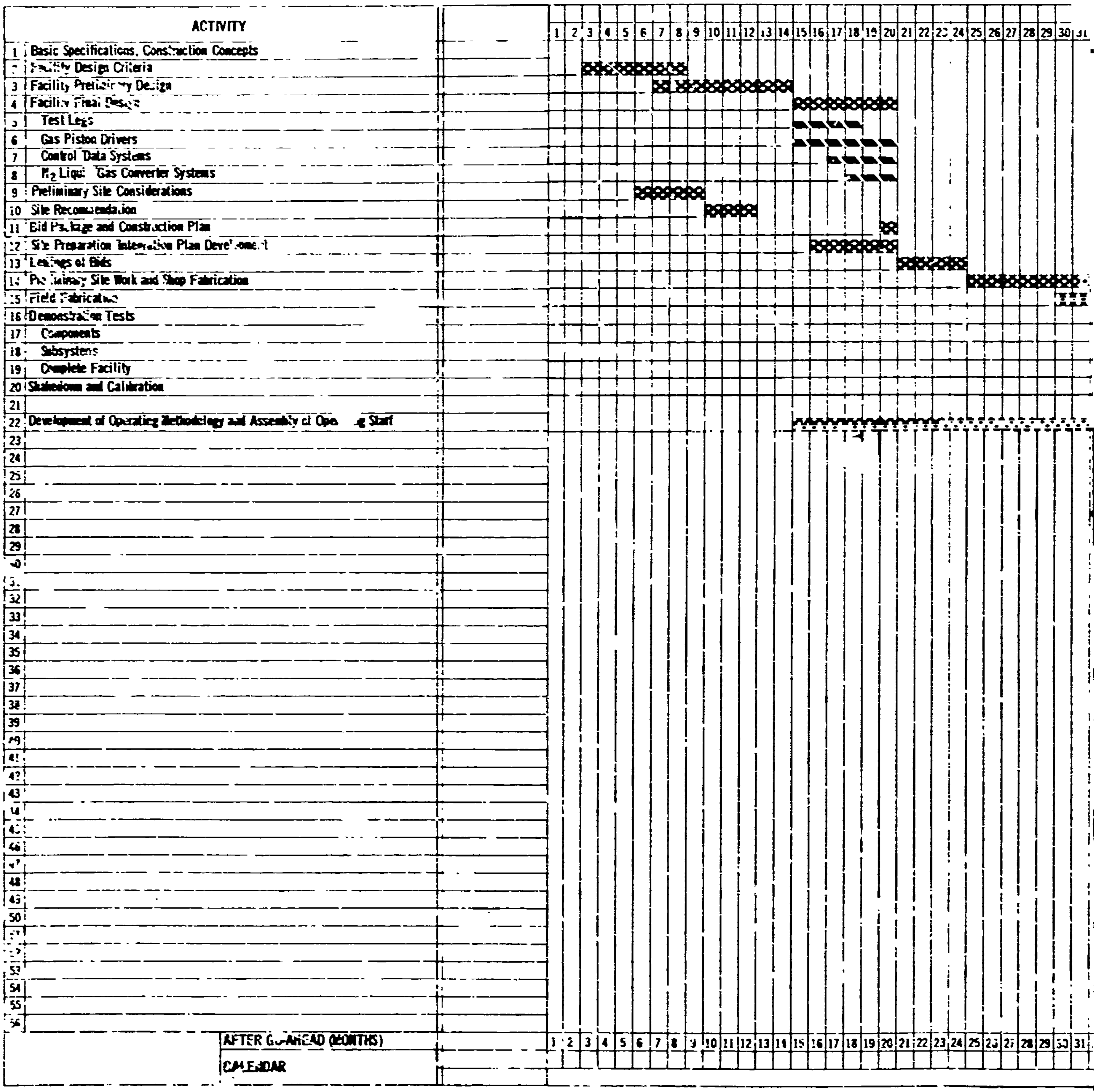
Schedule . . . . 55 Months

At the expense of slightly increased total cost, the annual costs can be reduced by initiating a stretched out program where the initial facility performance is less than the final goal.

The primary cost stretch out alternative available for GD7 is to construct the Mach 10-13 hypersonic test leg at some time after the Mach 8-10 test leg. All subsystems and the laboratory and office building are common to both test legs and would be provided during the initial acquisition, except the instrumentation system for the Mach 10-13 leg. The entire facility would be designed as an entity according to the schedule in Figure 5-5, but actual construction of the test legs would be sequential. The initial construction should be complete in 50 months including shakedown and calibration, and approximately 24 months would be required to complete the second increment. At a total facility cost of $29.0 million, there is not really much annual cash flow reduction by this schedule stretchout compared to the reductions possible in some of the larger facilities. The cost and schedule for this alternative is then:

Cost		
Mach number 8 to 10 leg		$15,480,000
Mach number 10 to 13 leg		$13,520,000
	Total	$29,000,000
Schedule		
Mach 8-10 leg initial acquisition		50 Months
Mach 10-13 2nd increment requiring an additional.		24 Months
	Total	74 Months

FIGURE 5-5
ACQUISITION SCHEDULE – GAS DYNAMIC RESEARCH FACILITY – GD7



FOLDOUT FRAME 1

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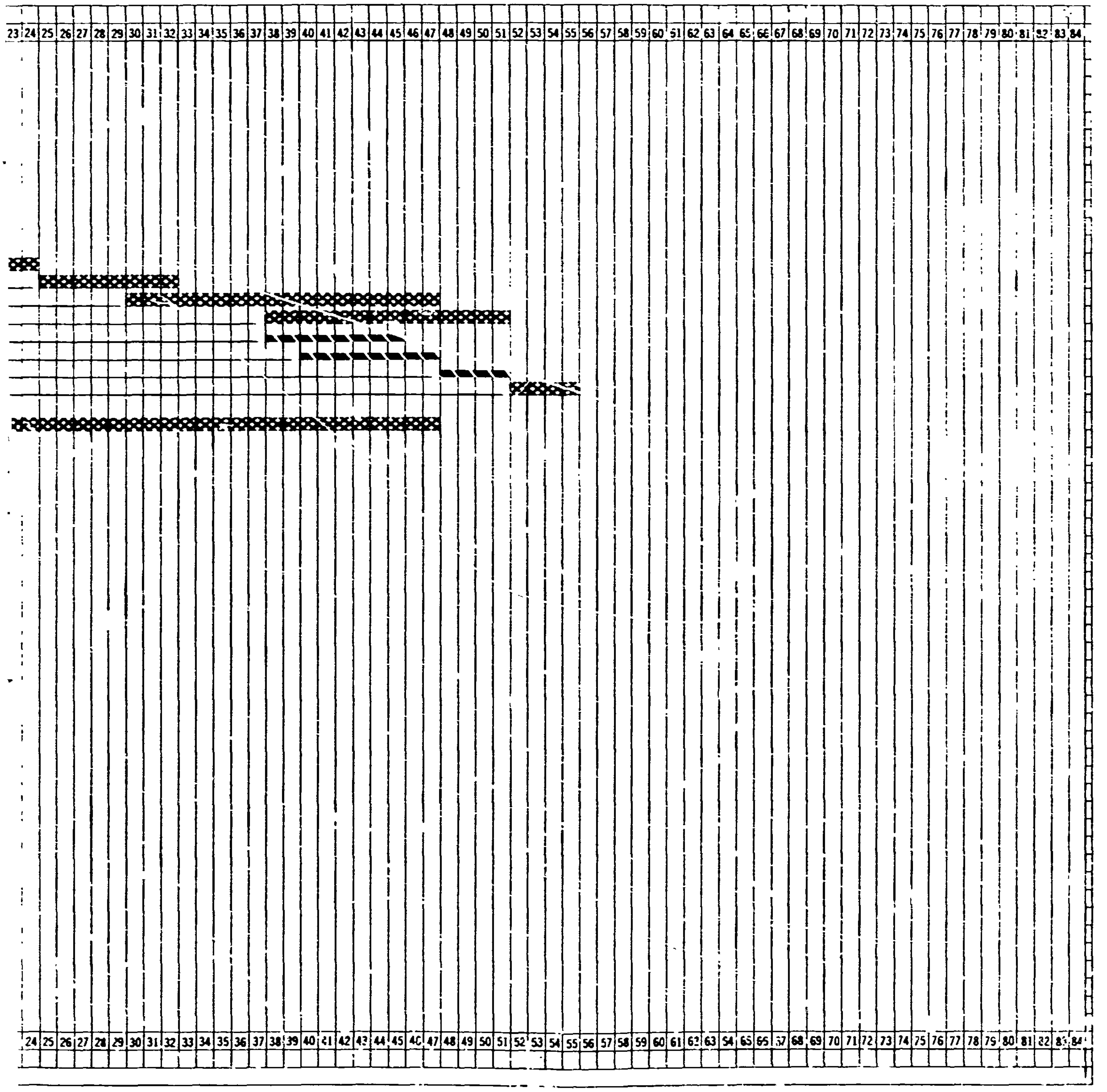
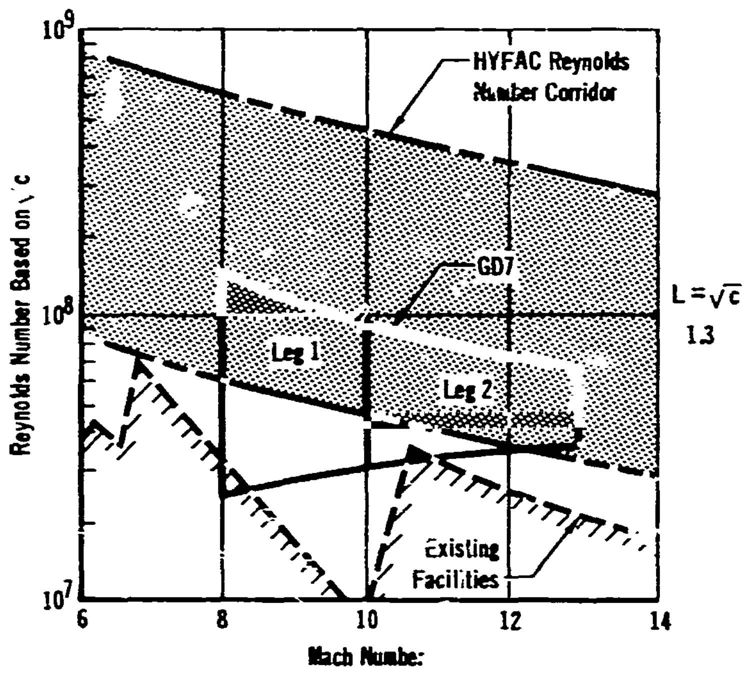


FOLDOUT FRAME 2

5.6 EVALUATION SUMMARY

As for the Polysonic Wind Tunnel (GD20), analysis of the capabilities of existing facilities in the Mach number range of GD7 showed a serious deficiency for large aircraft flying a high dynamic pressure trajectory (This discussion is presented in Section 4.6, and will not be repeated here). The following sketch illustrates the Reynolds numbers required for a 300 ft (91 m) long aircraft flying trajectories bounded by 2000 psf (95,700 N/m^2) and 200 psf (9570 N/m^2) dynamic pressure limits, compared with the capabilities of existing facilities and of GD7.



The Reynolds number criteria established as a design goal for the gasdynamic facilities was 1/5 of the maximum flight Reynolds number. An additional factor in the judgements affecting the design criteria for the gasdynamic research facilities was that the simulation level selected for the facilities should represent a significant increase in Reynolds number simulation level over existing facilities. The performance envelope defined for GD7 satisfied both these criteria.

During Phase III, a final list of 278 Research Tasks, each task being a subset of the 78 Research Objectives, was defined. This list of research tasks was used to determine the research potential of each candidate research facility considered during Phase III. Details of this analysis and evaluation are contained in Volume IV, Part 3.

GD7 was identified to have contributions to many Research Objectives. Research Objectives were written for the entire Mach number range for the HYFAC operational vehicles. Only research applying to the L2 and M2 vehicles applied to GD7, since the other vehicles do not reach the minimum Mach number of GD7, whereas GD20 contributes to the Research Objectives for all the HYFAC vehicles. In terms of research capability, GD7 was evaluated as providing about a 40% increase over existing facilities in its Mach number range. Considering the already demonstrated capability of existing facilities, this judgement reflects the need for high Reynolds number research capability in the hypersonic flight regime, and the influence that problems in this flight regime can have on the design performance of hypersonic aircraft. This facility therefore is very relevant to the research and development capability required for potential operational aircraft. GD7 has application not only to aircraft types characteristic of the HYFAC study, but can provide a significant increase in research capability for tactical and strategic military systems.

The following matrix is representative of the capability of GD7

Increased Research Capability in the Area of:	HYFAC	Strategic Vehicles	Tactical Missiles	Interceptor Missiles
Nozzle Thrust Minus Drag	●	●	●	●
Inlet Development	●		●	●
Shock/Boundary Layer Interactions	●	●	●	●
Aeroelastic Effects	●	●	●	●
Maneuvering Maximum Lift Coefficient	●		x	●
Stability and Control	●	●	●	●
Power Effects	●	x	●	●

Contribution: ● Significant
x Limited

It should be noted that, in the case of the missile systems, required test angles of attack are appreciably less than for aircraft, enabling the use of a much longer model relative to the test section height than possible for aircraft.

The conservative model sizing rule used here for aircraft has been $L = \sqrt{C}/1.3$. For slender missiles with limited angle of attack ranges, L can be on the order of $2\sqrt{C}$ or approximately 2.6 times the length of an aircraft model, with a resultant increase in test Reynolds number. Likewise, models which represent aircraft considerably smaller than the nominal 300 ft (91 m) HYFAC aircraft can be tested at Reynolds numbers much closer to full scale flight values (dependent on the full scale vehicle flight corridor) than the 1/5 value obtained for the HYFAC airplanes.

Figure 5-6 summarizes the performance, costs, development assessment, and design characteristics of GD7. The numerical confidence level associated with the development assessment of GD7 is equal to 4.36. This numerical evaluation is consistent with a subjective evaluation that GD7 represents a larger version of equipment currently in operation, as based on the definitions in Section 2.4

The low development risk associated with this facility implies that although large in size, it does not represent a major challenge to the current fabrication technology level, and that the major risk would probably be associated with the large, high pressure gas piston drivers. Its operating principles have been demonstrated in moderate sized hypersonic wind tunnels. This particular facility can provide a significant increase in the research capability associated with large aircraft flying high dynamic pressure flight paths. As pointed out previously, the need for such Reynolds number capability is dominated by large airbreathing launch systems, transports, and military systems flying low altitude, acceleration flight paths. In order to have the necessary confidence to proceed with the development of such vehicles, a facility having the capability of GD7 will probably be necessary.

FIGURE 5–6
PERFORMANCE AND FACILITY SPECIFICATIONS FOR GD 7

Test Section Dimensions	10 Feet Dia. (3.05 m)
Mach Number	8 to 13
Stagnation Pressure	300 to 18,000 psia (206 to 13,000 N/cm^2)
Stagnation Temperature	1200 to 2500°R (700 to 1300°K)
Minimum Run Time	1 to 4 Seconds
Time Between Runs	1 Hour Average 2 Hour Maximum

Cost - $26,606,000
Confidence Level Assessment - 4.36 on a scale from 1 to 5, where 5 represents Low Risk Existing Equipment Technology, and 1 represents High Risk Theoretically Predicted Technology.

6. COMPOUND TURBOMACHINERY TEST FACILITY (E20)

E20 is a continuous engine test facility which provides full flight duplicated conditions to two test legs at flight Mach numbers up to 5.5. Traditional direct connect testing on 100,000 lb (485,000 N) thrust class engines is done in the direct connect test leg. A second test leg, embodying a novel testing scheme, is provided. This test leg, the free-jet test leg, is sized to accommodate hypersonic inlet and engine packages for inlet/engine integration studies of approximately 50,000 lb (222,500 N) thrust engines.

The facility was specified to provide full flight duplication in the direct connect mode throughout the flight Mach range of 0.3 to 5.5, as exemplified by Figure 6-2, and free-jet testing at angles of attack throughout the flight Mach number range of 0.3 to 5.0.

The flight corridor chosen for the facility, in combination with the requirement that full flight duplicated conditions must be provided, completely defines the range of stagnation pressures and temperatures required for the facility. These requirements, for both direct connect testing and free-jet testing, are shown in Figure 6-3c. The parameter most directly affecting facility test capability and cost, the mass flow schedule, is a function of the specific mass flow requirements of the engines to be tested. Definition of this requirement was an important part of the Phase III study.

Direct connect testing represents the lowest cost method of obtaining continuous testing. In this test mode, the engine is connected directly to a subsonic duct, or bellmouth, which provides the engine with the correct flow rate at the duct stagnation pressure and temperature which would exist in the aircraft inlet duct after the flow had been decelerated to a subsonic Mach number. The cost of this method is less than that of freejet testing because much lower maximum facility stagnation pressures are required, and no mass flow rate is provided except that actually needed to go through the engine. This greatly reduced cost is obtained at the expense of full similitude of dynamic conditions in the flow provided to the engine. These factors, which affect inlet duct/engine compatibility, are typified by pressure recovery, distortion and turbulence, and can only be evaluated in free-jet testing of the inlet/engine combination throughout the full flight trajectory and angle-of-attack range. Evaluation of static flow distortions produced by the inlet duct system can be done by testing large scale inlet wind tunnel models. The static distortions measured can then be produced by distortion screens in the [illegible] connect facility.

Some [illegible] to produce the flow distortions and correct boundary layers [illegible] the direct connect facility with a two-dimensional, single [illegible] number nozzle in place of a subsonic bellmouth. This [illegible] mode of testing, wherein a low supersonic Mach number flow [illegible] of the actual airplane duct system which then feeds the engine [illegible] system is used, from just forward of the duct throat to the e[illegible], a better representation of the effects of actual duct con[illegible] temperature on flow velocity profile and boundary layer growth is obtained.

The free-jet test leg has been re-sized from its Phase II description to operate within the limits of the facility major systems which are required by the direct connect test leg. A nozzle size of 8 ft by 4.5 ft (2.4 by 1.4 meters) is provided.

In free-jet testing, the actual freestream Mach number is developed in the nozzle, and the entire inlet duct/engine combination is tested. This type of testing is the most costly method, since the full freestream stagnation pressure must be obtained, and a considerable surplus of facility mass flow must be provided over that mass flow which actually goes into the engine. Three different facility schemes can be used for free-jet testing.

The first method is the propulsion wind tunnel, which has a nozzle test section large enough to accept the inlet/engine combination at maximum angle-of-attack. Considerable nozzle height must be provided in order that sufficient room is left between the inlet and the ceiling and the exhaust nozzle and the floor at the test section to avoid interference effects. This method, although most satisfactory from a technical standpoint, has not been considered because of the very large nozzle size and mass flow rate needed in comparison to the other two methods, which are not small in themselves.

The second method is a test cell where the inlet/engine is mounted on a fixed thrust stand and the nozzle is pitched. This method is used on small facilities with success and has an advantage in that the exhaust piping of the engine can be non-movable. In the case of E20, however, the large Mach range requires a very long and heavy flexible plate nozzle with water cooled walls. The weight and complexity of this system make it entirely impractical to pitch the nozzle.

The third method, which has been chosen for the free-jet test leg, uses a large flexible plate water cooled nozzle, fixed in position. An inlet/engine model is mounted within a test section, whose ceiling and floor remain parallel while pitching with the inlet/engine. An articulated diffuser moves up and down with the test section and dumps the flow into a plenum chamber. A collector in the plenum chamber is connected to the exhaust piping. The top and bottom plates of the diffuser can move differentially with respect to each other, as well as together, so that optimum diffuser efficiency can be obtained at all Mach numbers.

In summary, the free-jet test leg is capable of doing performance and PFRT tests on a continuous basis, and with full duplication of flight stagnation temperatures and pressures, over the Mach number range of 0.3 to 5.0. It is especially suited to testing inlet/engine compatibility problems, using inlets and engines of approximately 50,000 lb (222,500 N) thrust.

The following sections describe the work done to refine the facility design and performance, the results of this refinement in terms of facility component descriptions and costs, considerations of safety, and site criteria, an assessment of the critical areas in developing the facility, an analysis of the total facility acquisition schedule, and a summary of the facility evaluation.

6.1 REFINEMENTS IN DESIGN AND PERFORMANCE

The work done on this facility during Phase III was concentrated in three areas:

- o Re-definition of engine sizes to be accommodated
- o Resizing of all facility components based on engine definitions
- o Estimation of more realistic hardware specifications and costs

The following tasks were performed in order to satisfy these requirements:

1) Maximum engine sizes were defined, in consultation with the HYFAC propulsion technologists. Supersonic turbojets, turbofans, turboramjets and subsonic turbofans were specified in order to define a facility mass flow schedule adequate for the engine testing needs of 20 to 30 years from now.

2) The total inlet direct connect flow requirements of the facility were calculated, based on the engine requirements and the HYFAC flight corridor. This requirement is shown in Figure 6- 3 a, b, c.

3) Having sized the weight flow requirements, a detailed analysis of compressor and exhauster requirement was done. A by-product of this work was an analysis of the flow cooling required to reduce the exhauster inlet flow temperatures to acceptable levels and reduce exhauster inlet volume flow. It was found that owing to the combinations of compressor and exhauster capacity required at any given test point, a 1/3 reduction in total capacity could be achieved by designing a combined compressor/exhauster plant, Specifications and costs of a plant fulfilling the developed requirements were worked out by Allis-Chalmers.

4) An analysis of the heater requirements was done, and a reasonable power limit was specified. A small portion of the low altitude, high Mach number flight corridor for the turboramjet engine was sacrificed at a cost saving of about $83 million.

5) Conversations with staff and operating personnel at AEDC were held with respect to possible use of existing systems at AEDC by E20. It was felt that a facility of such magnitude as E20 could not possibly share any utilities or support systems with existing facilities. Consequently, all E20 systems have been considered to be provided specifically for E20. It was also determined that the operating costs presented in Phase II were considered very high. The reason for this was that relatively high values of power utilization factor (U_P) and run utilization factor (U_R) had been used. Values which were more in line with those normally obtained in very large facilities were used in this phase as a result of the AEDC conversations.

6) Structural and mechanical layout of both test legs was done by Fluidyne, based the rough Phase II sketches and the Phase III requirements. This facility in particular benefitted from the expertise Fluidyne applied to their layouts. Test leg cost estimates were done using the Fluidyne drawings as a basis.

7) The free-jet leg was re-sized to fit the major support systems defined by the requirements of the direct connect leg. The transonic test region of the FJ leg was eliminated since it had little research value and imposed severe volume flow requirements on the exhausters. The size of the free-jet nozzle meeting these restrictions is 8 ft x 4.5 ft (2.4 x 1.4 m). These dimensions are about half the values used in the Phase II work.

8) Analysis of safety hazards to personnel, test article and facility were performed by Fluidyne, and procedures, safety interlocks, special subsystems, and control system rationale needed to operate the facility safely were described.

9) As the elementary cost analysis in Phase II showed, the costs of support systems were the dominating factor. In addition to obtaining much more sophisticated equipment requirements, costs of all equipment were estimated, where possible, by equipment manufacturers. These estimates are based on gross specifications and not a detailed engineering study of each individual component. The costs estimated by the vendors and manufacturers, therefore, are engineering judgements based on their industrial experience.

10) An analysis of the problems and risks associated with each major component and system of the facility was performed. A composite assessment for the entire facility was calculated. This assessment attempts to quantify the facility confidence level and identify major problem areas.

11) An evaluation of the facility was made, summing up its ability to perform the research tasks in relation to its acquisition and operating cost.

6.2 FACILITY DESCRIPTIONS AND COSTS

The E20 Compound Turbomachinery Research Facility is, like all continuous engine test facilities, basically a large plant capable of producing the required mass flows, pressures, temperatures, and altitude duplicated static test conditions to a test leg or legs. The magnitude of the major systems required, as well as their costs, dwarfs the specific dimensions and costs of the test legs. In fact, it is characteristic of such facilities, having provided the flow requirements through the construction of compressor plants, exhauster plants, heaters, refrigeration plants, flow and facility cooling systems, and the instrumentation and control complex required to operate these systems, that many test legs or cells having special test features can be placed in the circuit. In the case of E20, a straight-forward direct connect test leg and a unique form of free-jet test leg are provided. Figure 6-1 depicts schematically the general layout of E20, showing the major systems required to provide and condition the inlet and exhaust flows for the test legs. An actual overall design layout, not attempted in this study, should incorporate a piping layout which would allow the later addition of other test legs in a neat and simple manner, with no disruption of existing capabilities or test operations.

Two factors are the prime determinants of the definitions of the test legs and major facility systems, and thus their cost.

(a) The Flight Envelope to be Duplicated - For E20, this envelope is shown in Figure 6- 2. The boundaries for engines suitable for the various HYFAC operational airplanes are shown solid, and are essentially the dynamic pressures of 200 and 2000 psf (9570 and 95,700 N/m^2). An internal duct pressure limit of 150 psi (103 N/cm^2) is also used, this limit being equal to the maximum internal pressure that the MCAIR structural and propulsion technologists believe can be sustained in a duct which incorporates articulated ramps without excessive structural weight penalties. A typical flight boundary for subsonic aircraft is also shown since it is contemplated, even though such aircraft are not part of the HYFAC study, that an engine test facility plant capable of testing the large supersonic engines, being a very costly and large facility, should be capable of handling advanced technology engines of all types. Included in Figure 6-2 are two regions which will be unavailable for complete flight duplication. One region is bounded by the maximum facility air temperature and is determined by the temperature limits of the heaters. This is discussed in more detail in Section 6.2.5. Air flow rates and stagnation pressure can be duplicated in this region but true stagnation temperatures cannot be duplicated. The second region shown is unavailable only for the case of the turboramjet engine (described below), because of the chosen heater power limit. As will be described in Section 6.2.5, the TRJ engine imposed very severe heater power requirements on the facility and it was judged expedient to make a 50% reduction in the heater power limit, with a corresponding reduction in cost (about $83 million). The net effects of this rather drastic compromise is the elimination of the test area in question, for the TRJ only. The other study engines are not affected by this chosen power limit.

(b) The Engines to be Accommodated - As mentioned in Section 6.0, having chosen the flight corridors to be duplicated, the factor having the maximum impact on the design and size of the test legs, and more importantly on the specifications

FIGURE 6-1
PHYSICAL PLANT GENERAL ARRANGEMENT – E20

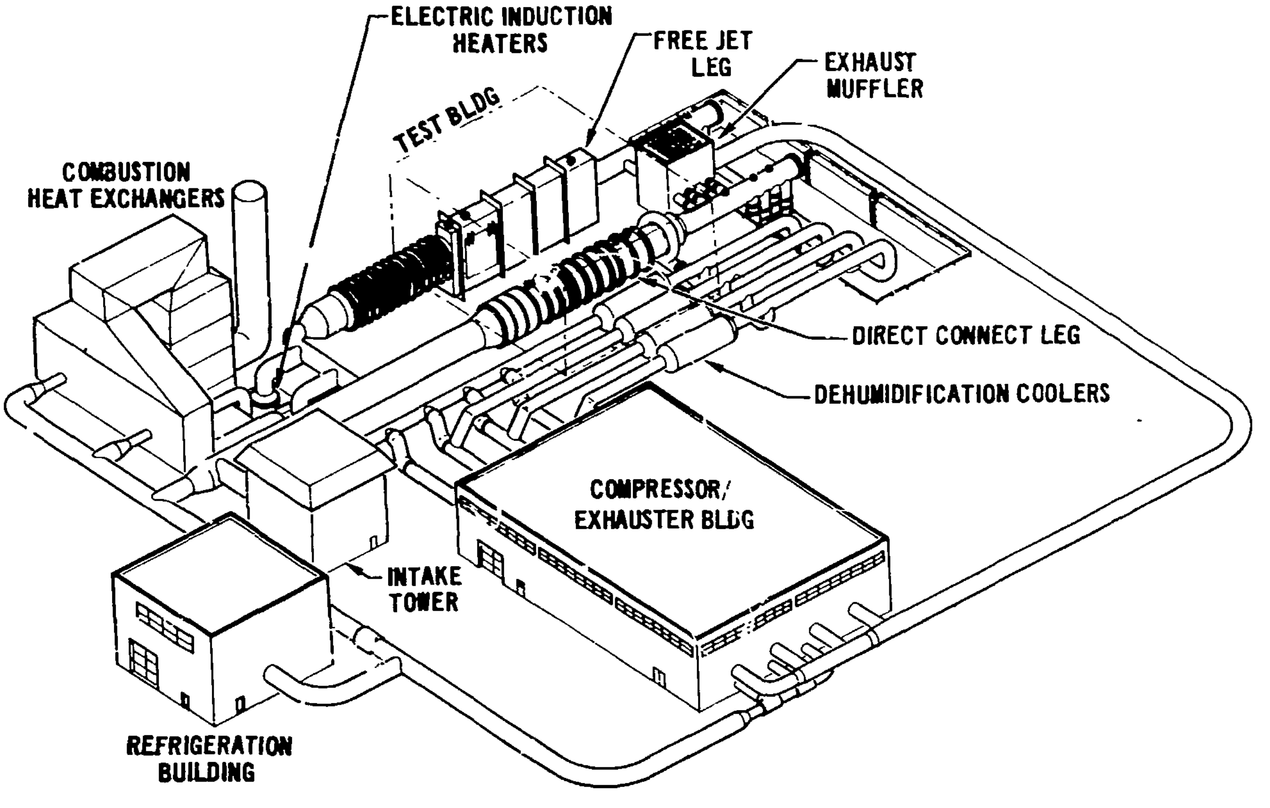
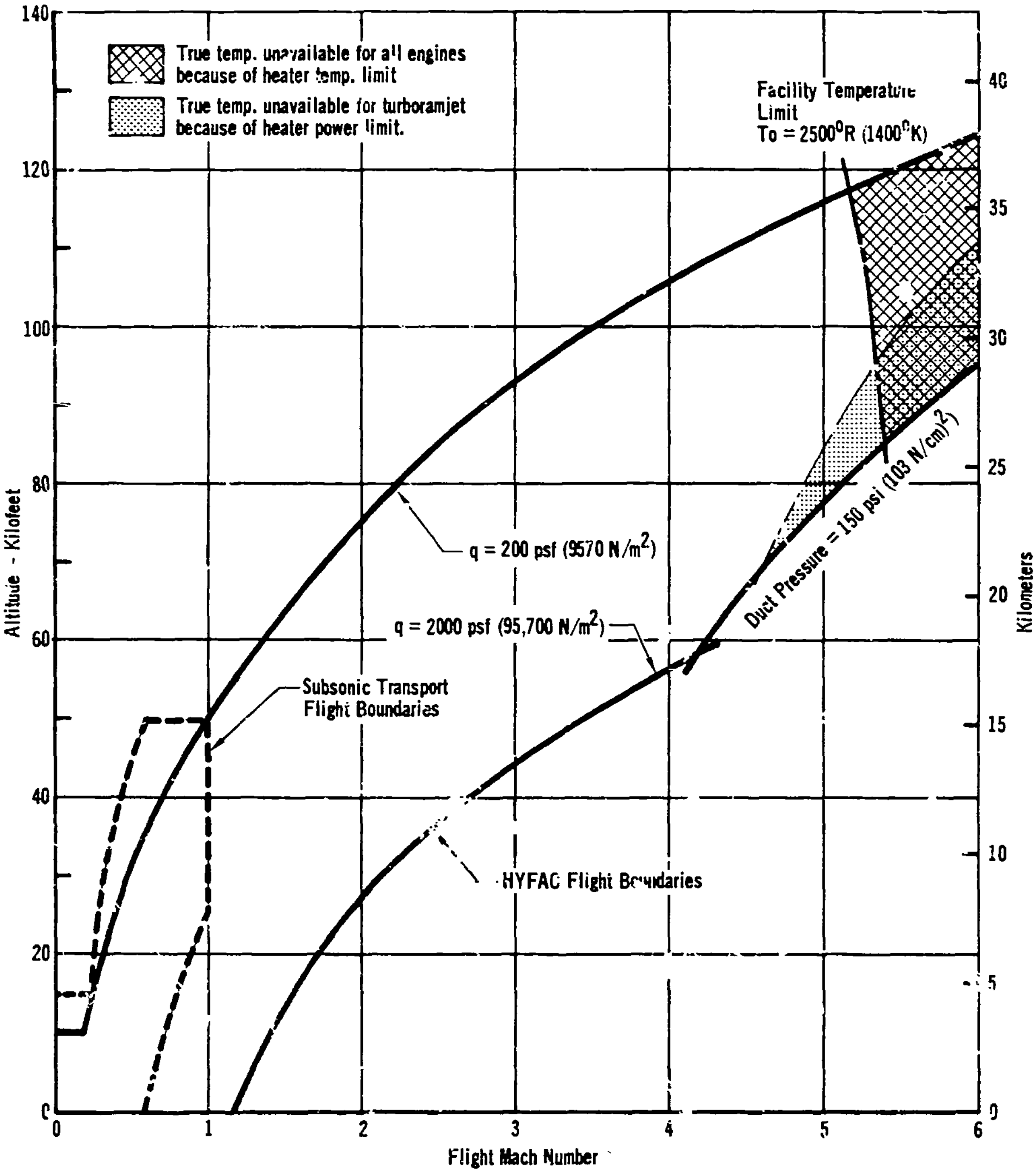


FIGURE 6–2
FLIGHT BOUNDARIES ASSUMED FOR E20 CANDIDATE ADVANCED TECHNOLOGY ENGINES



of the major facility systems, is the mass flow schedule required. The total facility mass flow requirements are based on the composite inlet flow requirements of the various engines to be tested.

The aid of the HYFAC study group propulsion technologists was enlisted in order to define the sizes of various engine types which might reasonably be expected to be operational within 20 or 30 years. No firm ground rules could be obtained or generated which would establish maximum feasible engine sizes based on physical laws or concepts like diminishing efficacy with increasing size, although it is reasonable to presume that some such natural size limiting factors do, in fact, exist. In the absence of any absolute engine size limitations, the growth trend of turbojet and turbofan engines were examined and a rough extrapolation was done to establish a reasonable engine size for each of several types. The engines upon which the facility requirements for E20 are based are:

(1) Turbojet, Mach 0 to 4.0, producing 100,000 lb (444,800 N) sea level static thrust on JP fuel or approximately 150,000 lb (668,000 N) thrust using LH_2 fuel.

(2) Low bypass turbofan, bypass ratio = 0.7, Mach 0 to 3.0, producing 100,000 lb (444,800 N) sea level static thrust on JP fuel and approximately 150,000 lb (668,000 N) thrust using LH_2 fuel.

(3) Turboramjet, Mach range 0 to 6.0, producing 100,000 lb (444,800 N) sea level static thrust on LH_2 fuel.

(4) Subsonic turbofan, bypass ratio = 8, Mach 0 to 1.0, producing 60,000 lb (267,000 N) sea level static thrust on JP fuel.

Published engine mass flow characteristics of smaller engines of each type were used to establish their mass flow characteristics for the specified HYFAC or subsonic transport flight boundaries, and these curves were scaled up corresponding to the thrust levels of the four defined engines.

These inlet flow requirements for the four defined engines are shown in Figure 6-3 a, b, and c. Figure 6-3a shows the stagnation pressure required for direct connect testing versus mass flow. The composite of the four engine requirements established the total facility inlet requirements. Also shown on this figure is the requirement of the free jet test leg with a nozzle size of 8 ft x 4.5 ft (2.4 m x 1.4 m). These nozzle dimensions were chosen specifically so that the free jet leg could operate using the major facility systems as defined by the direct connect leg. In other words, the free jet leg is considered an adjunct to the main test capability provided by the direct connect leg, and no extra costs, except for the test leg costs, are incurred in any of the major systems because of the free jet leg. Figure 6-3b shows stagnation temperature requirements versus mass flow for the four engines and the free jet leg. This plot shows the facility heater temperature and power limits (described also in Section 6.2.4 and 6.2.5). The shaded zones, described before with respect to the flight corridor, affect only the TRJ engine as defined. Figure 6-3c shows stagnation pressure versus stagnation temperature. The entire region required will be provided, up to the heater temperature limit.

FIGURE 6-3
INLET FLOW REQUIREMENTS FOR THE DEFINED ENGINES AND THE FREE JET TEST LEG

a. Stagnation Pressure and Mass Flow

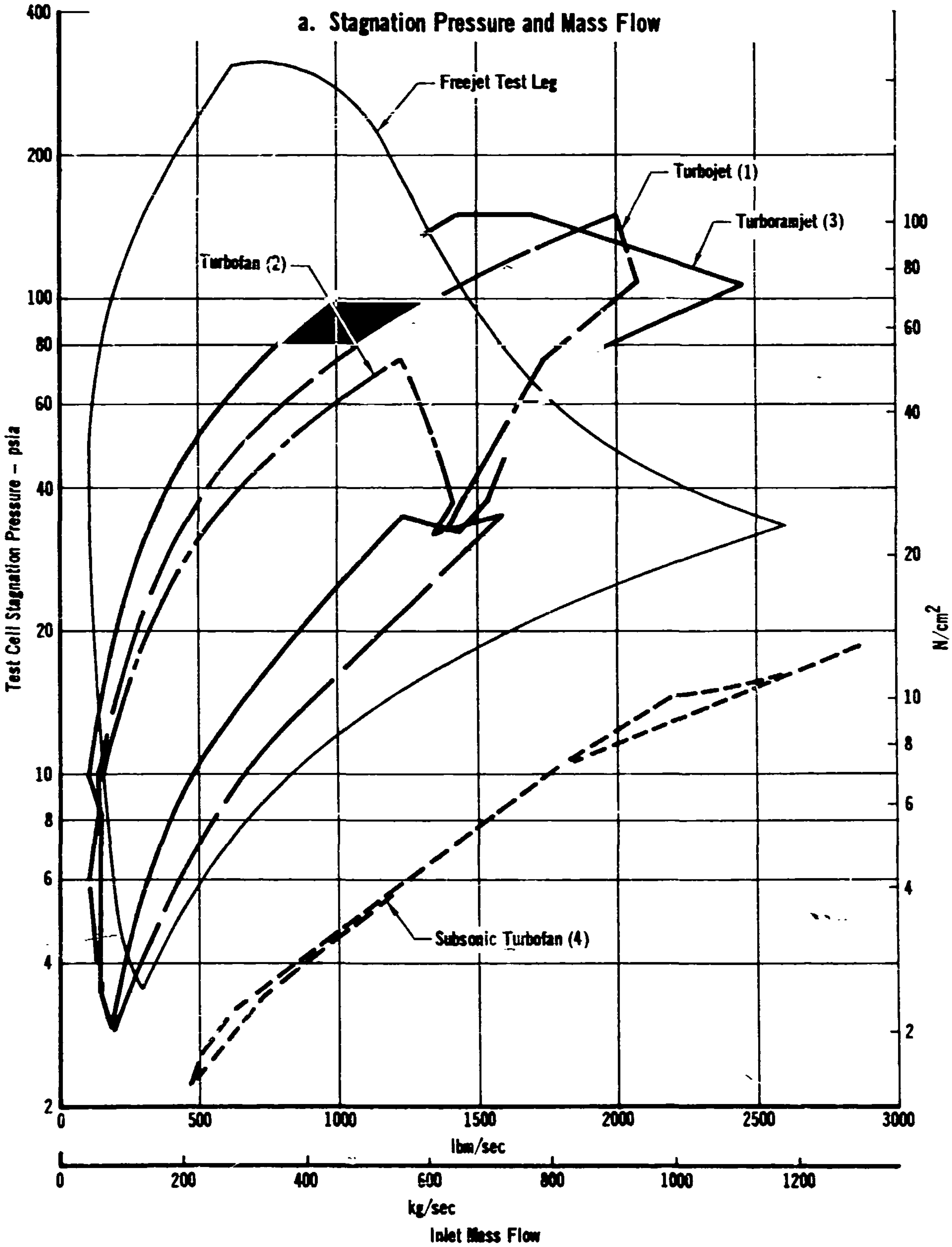


FIGURE 6-3 (Continued)
INLET FLOW REQUIREMENTS FOR THE DEFINED ENGINES AND THE FREE JET TEST LEG
b. Stagnation Temperature and Mass Flow

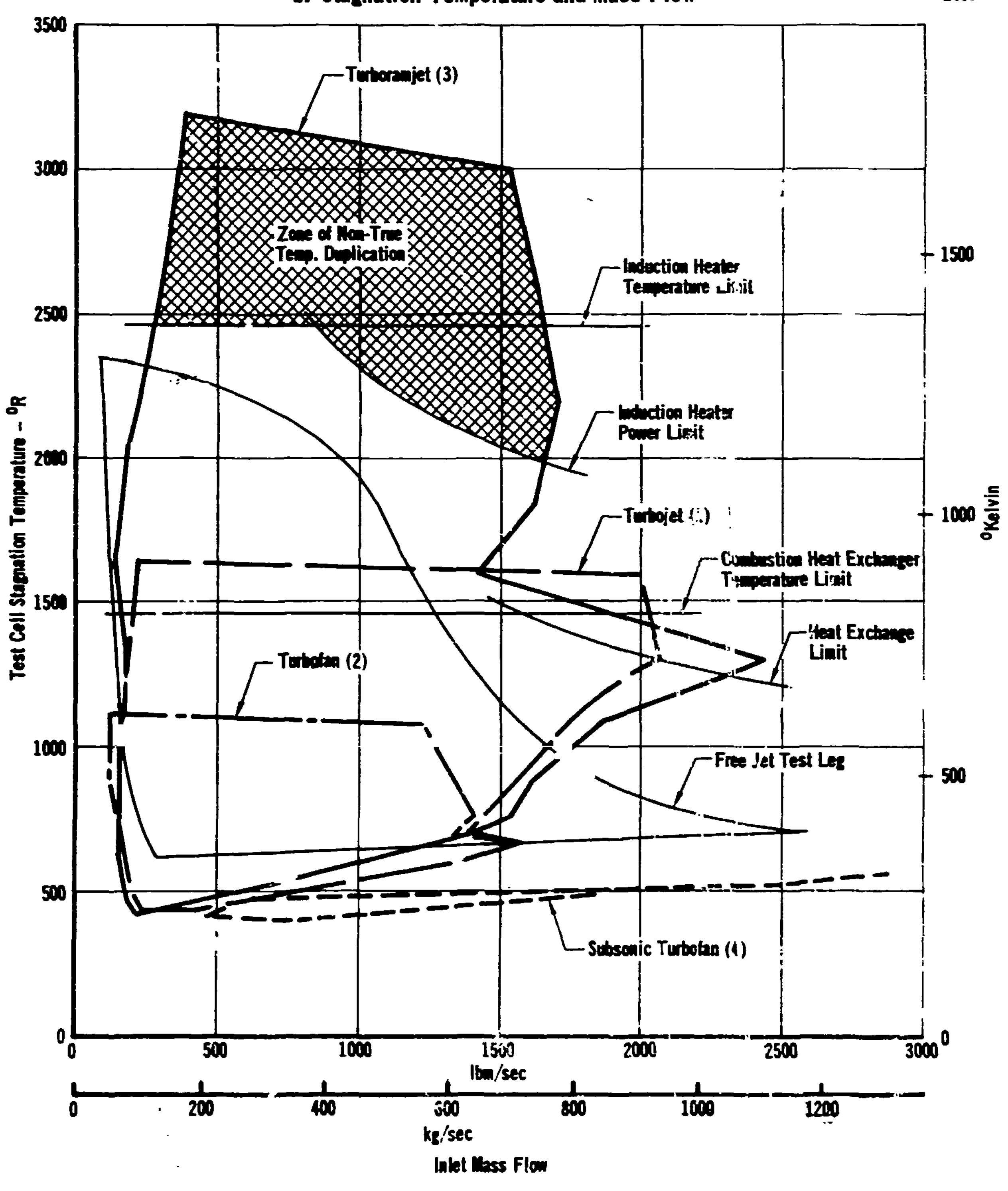
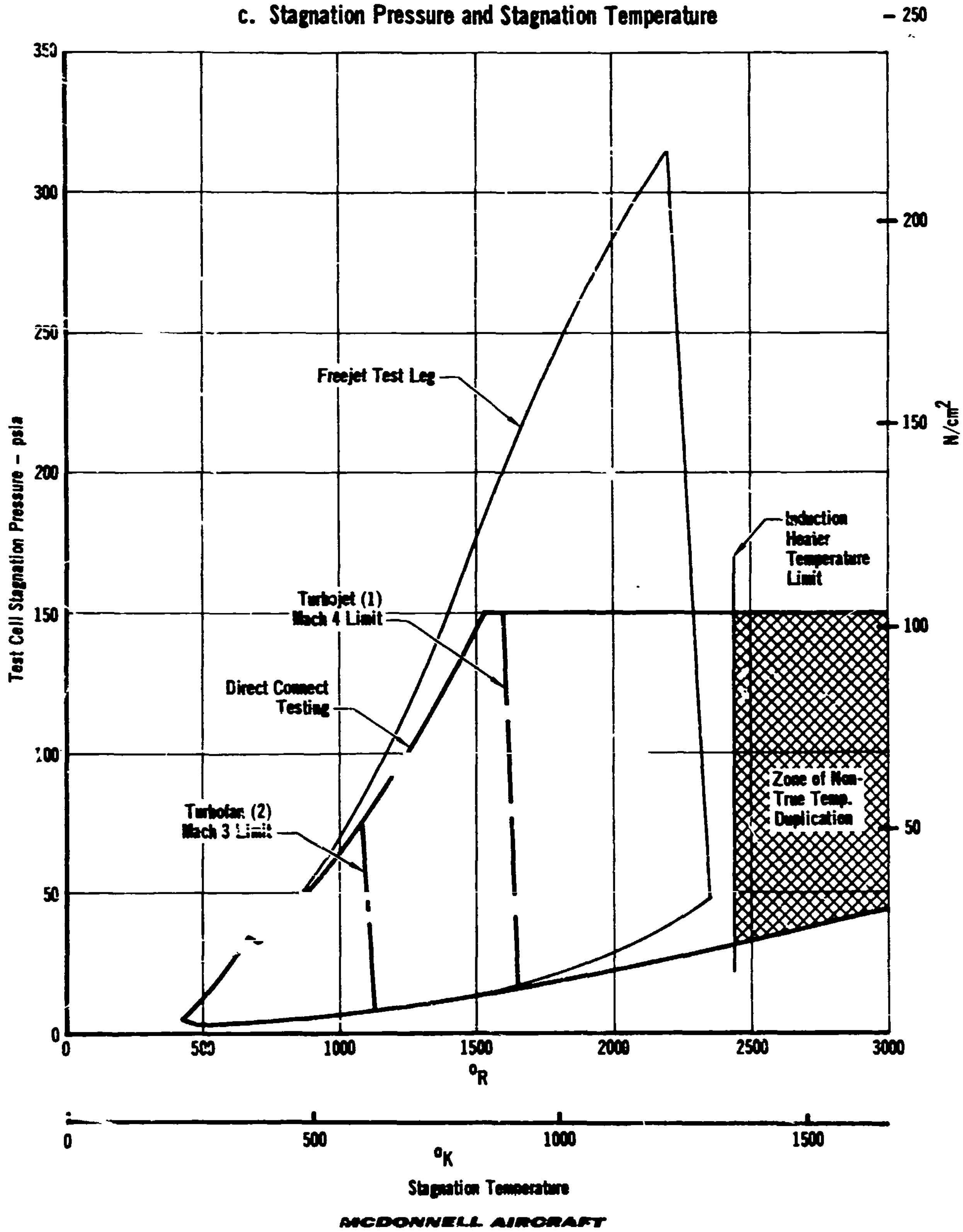


FIGURE 6-3 (Continued)
INLET FLOW REQUIREMENTS FOR THE DEFINED ENGINES AND THE FREE JET TEST LEG

c. Stagnation Pressure and Stagnation Temperature



These inlet flow requirements were used as the basis for calculating the requirements for the major facility systems. The following sections describe the test legs, the compressor/exhauster plant, the heaters, the spray cooling and dehumidification cooling system, the refrigeration plant, and present a cost summary of the facility.

6.2.1 DIRECT CONNECT TEST LEG - This test leg is basically an extension of traditional direct-connect engine testing technology to the large turbojet, turbofan, and turboramjet engines defined in Section 6.2.

Mechanical and structural details of the direct-connect test leg are shown in Figures 6-4 and 6-5, while Figure 6-1 presents an isometric view of the entire facility showing the relationship of the two test legs to the support systems.

This test leg is designed to provide continuous, subsonic duct flow to the engine for performance and PFRT testing. An additional testing capability is provided by the installation of a modified direct-connect device. This device is shown in the lower arrangement in Figure 6-4, and consists of a two-dimensional flexible supersonic nozzle connected to a portion of the actual airplane duct. The nozzle duplicates a supersonic Mach number inside the airplane inlet, downstream of one or two compression shocks. The nozzle can be set at a nominal Mach number and given small Mach changes on a scheduled time basis to evaluate the response of the engine to incremental velocity changes. Incorporation of an actual portion of the duct with the use of the same materials gives a better representation of duct boundary layer and velocity profile than straight direct connect testing.

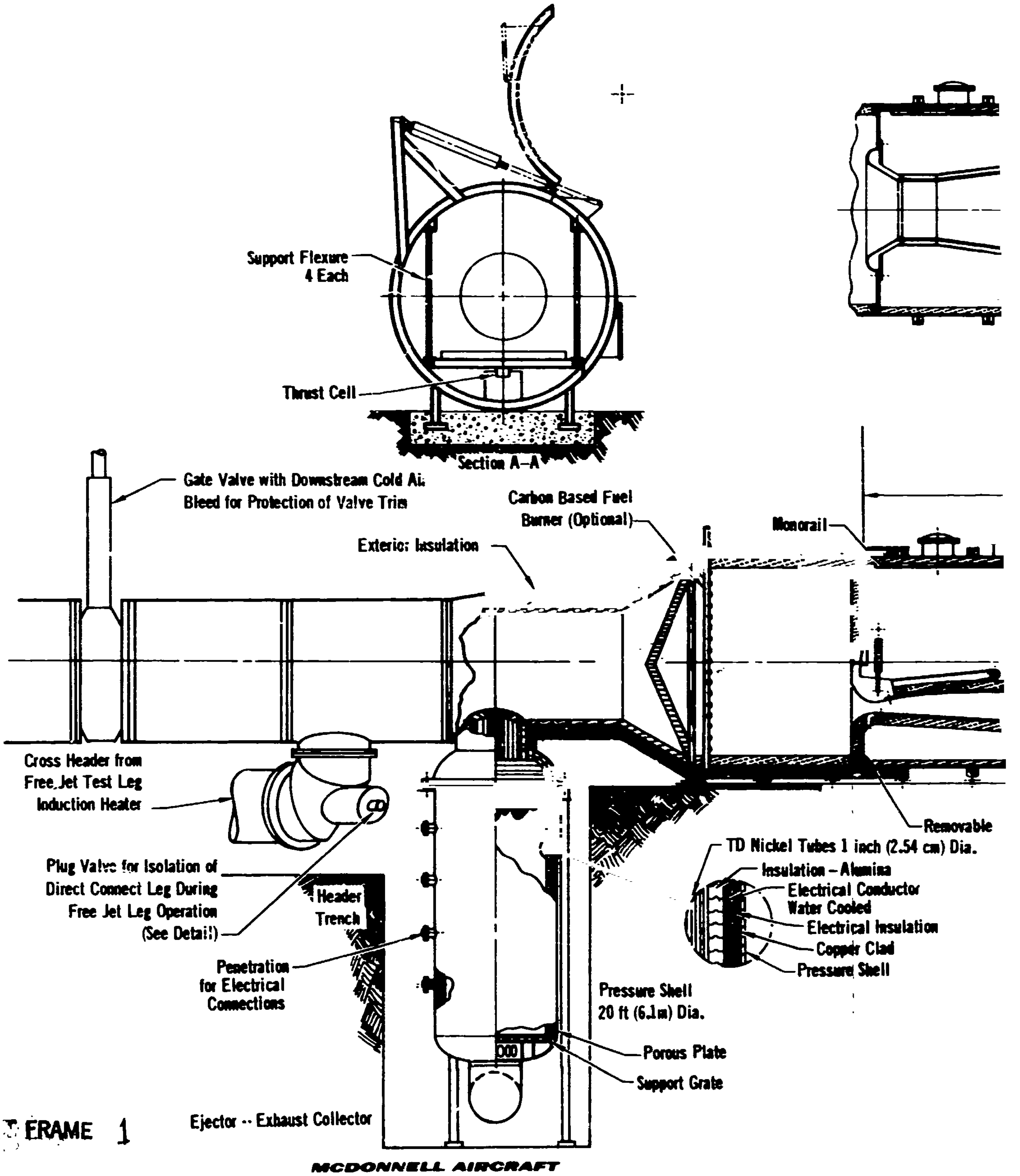
The test leg is connected by a large system of piping and valving to a compressor/exhauster plant, a refrigeration plant, a heater system, a cooler system and an intake tower and exhaust muffler. The system is designed to operate in a wide variety of configurations. For instance, inlet flow can be direct from the atmosphere or from the compressors, heated or cooled. The facility can exhaust straight to the muffler or through the coolers and exhausters to the muffler, dependent on the test conditions being run. This flexibility of operation is required by the wide range of altitudes and Mach numbers specified by the HYFAC flight corridor, and is responsible for the extremely large system requirements compared to existing facilities.

Control of test conditions is accomplished by coordinating the configuration and outputs of all the major systems and is done on a continuous basis.

The remainder of this section is devoted to discussion of the design features of the direct connect test leg components, problem areas, safety considerations, and construction techniques.

The inlet piping of the test leg is arranged such that air from the compressor or atmosphere flows directly to the test cell. Isolation valving allows flow to enter directly from the compressor, cooled or uncooled, or through the heater system, which consists of combustion heat exchangers and electric induction heaters in series (Sections 6.2.4 and 6.2.5).

FIGURE 6-4
E20 TURBOMACHINERY TEST FACILITY – DIRECT CONNECT TEST LEG



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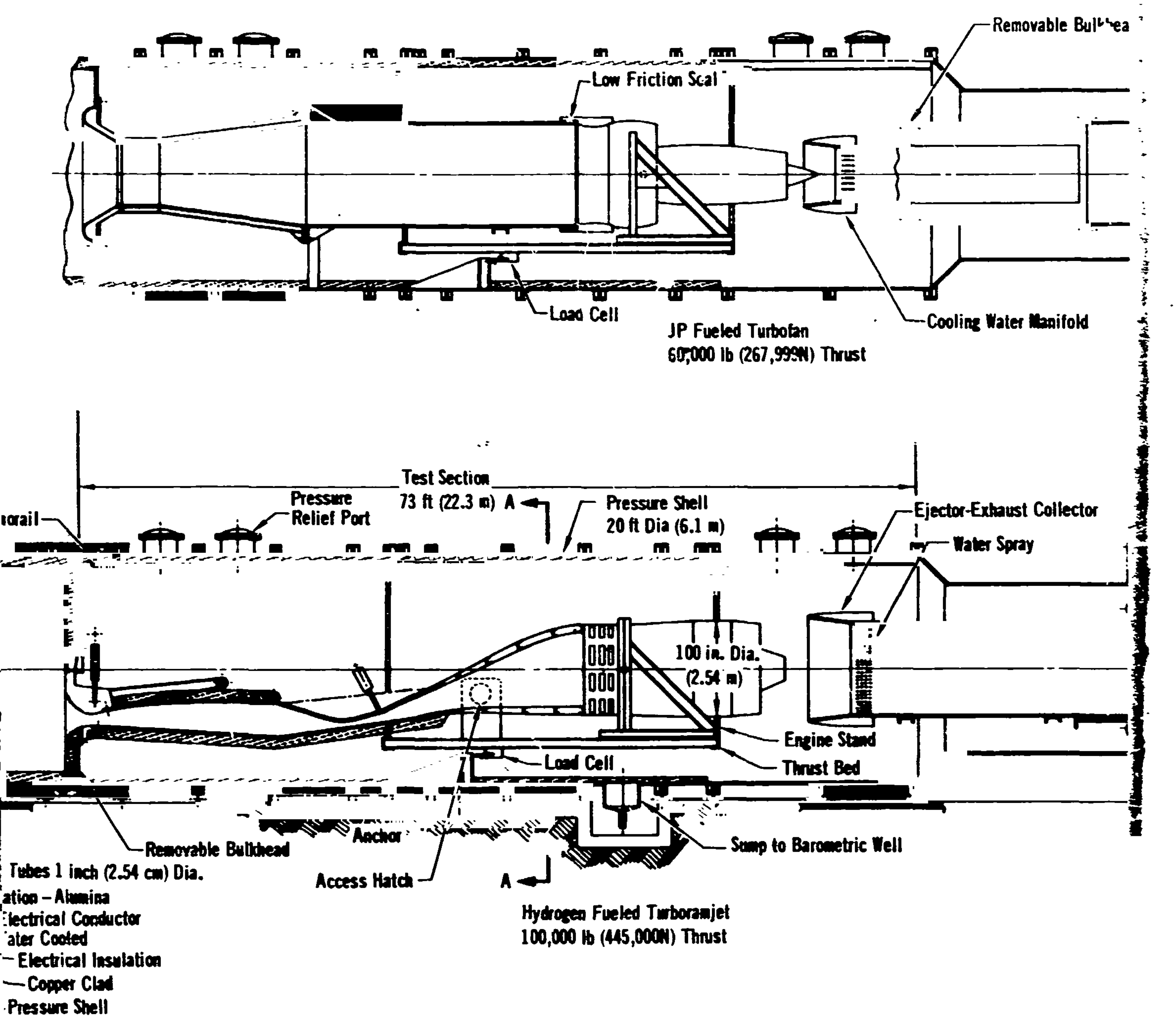
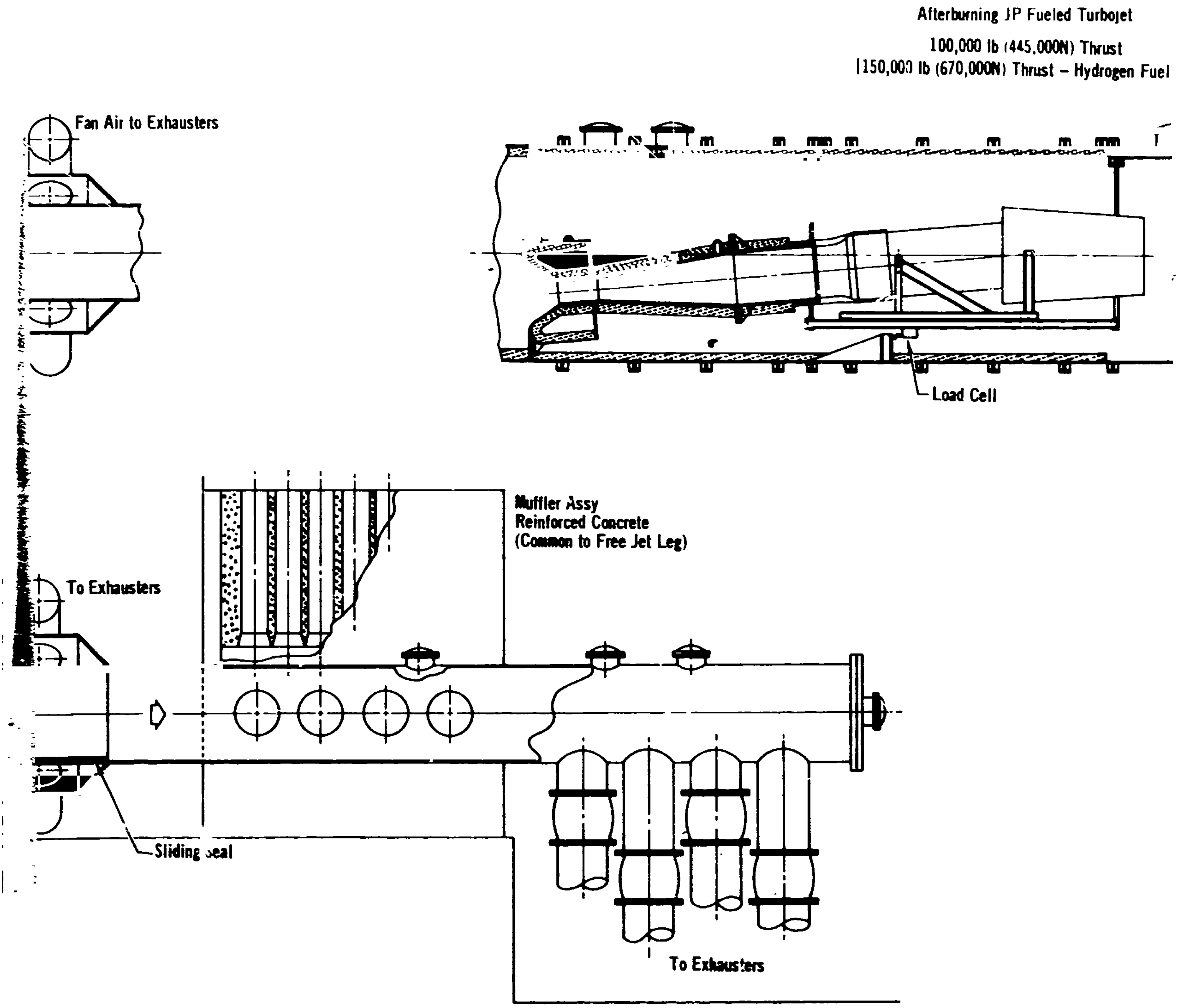


Removable Bulkhead
Low Friction Seal
Load Cell
Cooling Water Manifold
JP Fueled Turbofan
60,000 lb (267,999N) Thrust
Test Section
73 ft (22.3 m) A
Pressure Relief Port
Pressure Shell
20 ft Dia (6.1 m)
Ejector-Exhaust Collector
Water Spray
100 in. Dia.
(2.54 m)
Engine Stand
Thrust Bed
Load Cell
Removable Bulkhead
Anchor
Sump to Barometric Well
Access Hatch
A
Hydrogen Fueled Turboramjet
100,000 lb (445,000N) Thrust
Tubes 1 inch (2.54 cm) Dia.
ation – Alumina
lectrical Conductor
ater Cooled
Electrical Insulation
Copper Clad
Pressure Shell



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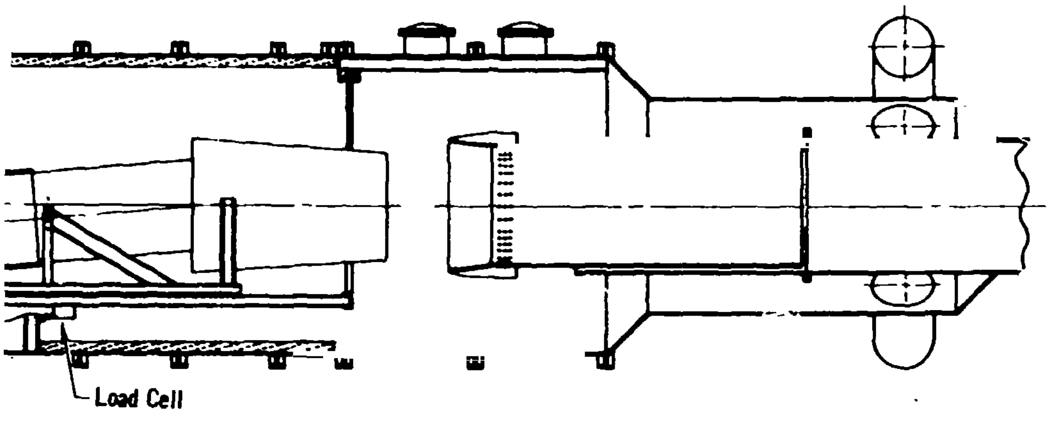
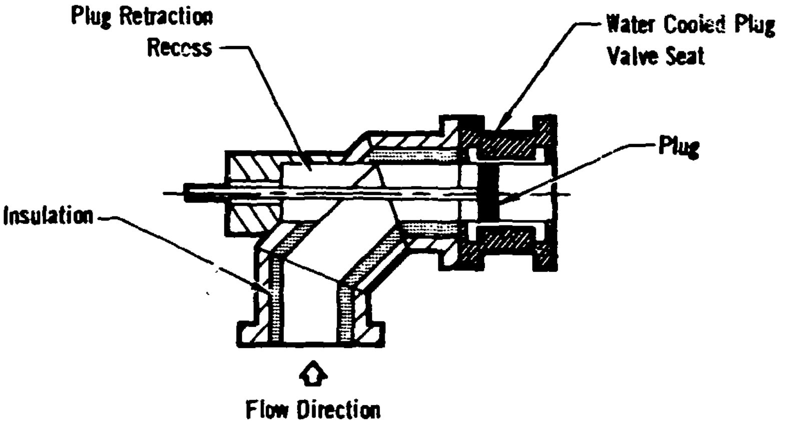
Afterburning JP Fueled Turbojet

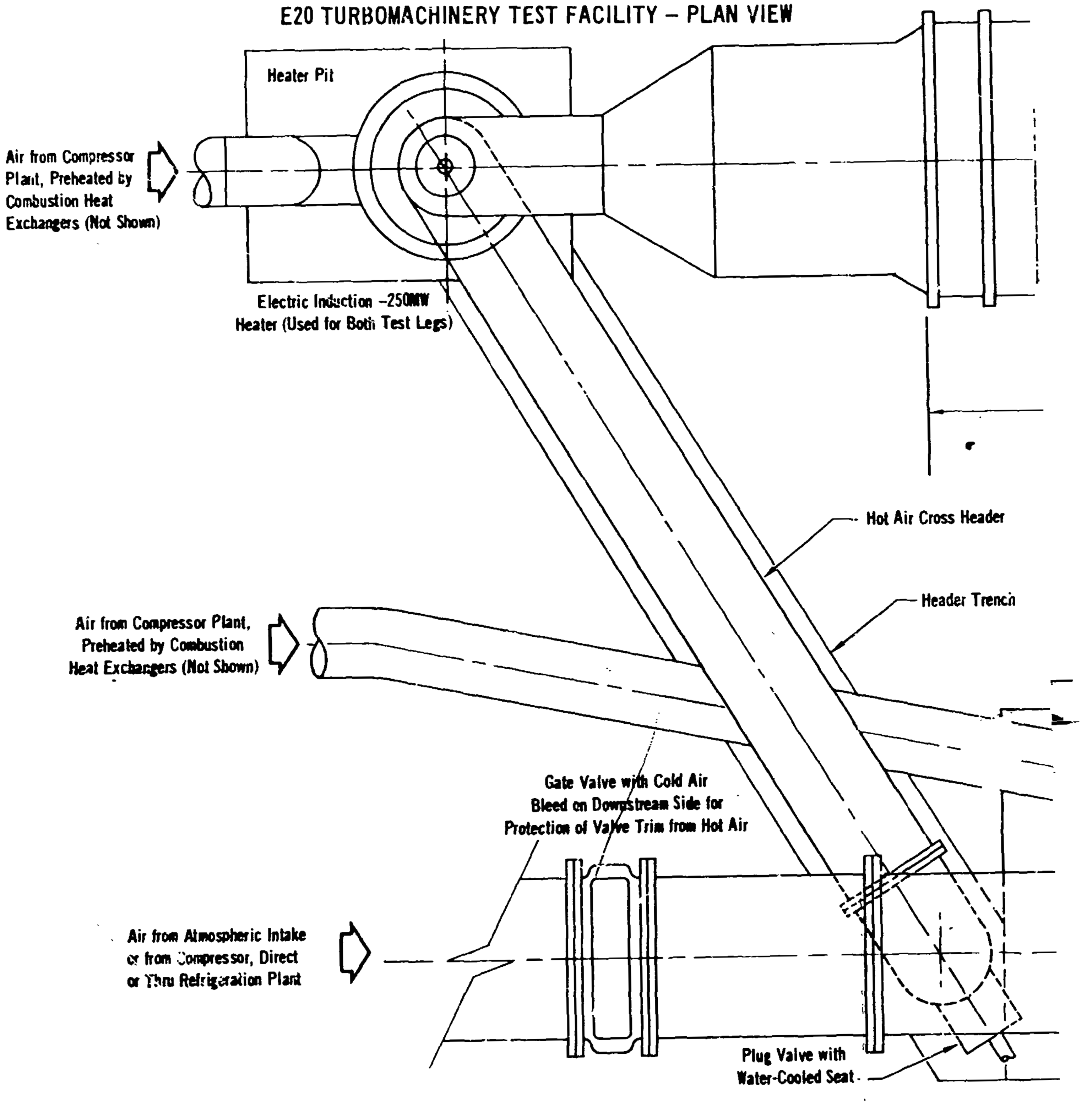
100,000 lb (445,000N) Thrust
50,000 lb (670,000N) Thrust – Hydrogen Fueled)





Plug Valve Detail

FIGURE 6-5
E20 TURBOMACHINERY TEST FACILITY – PLAN VIEW



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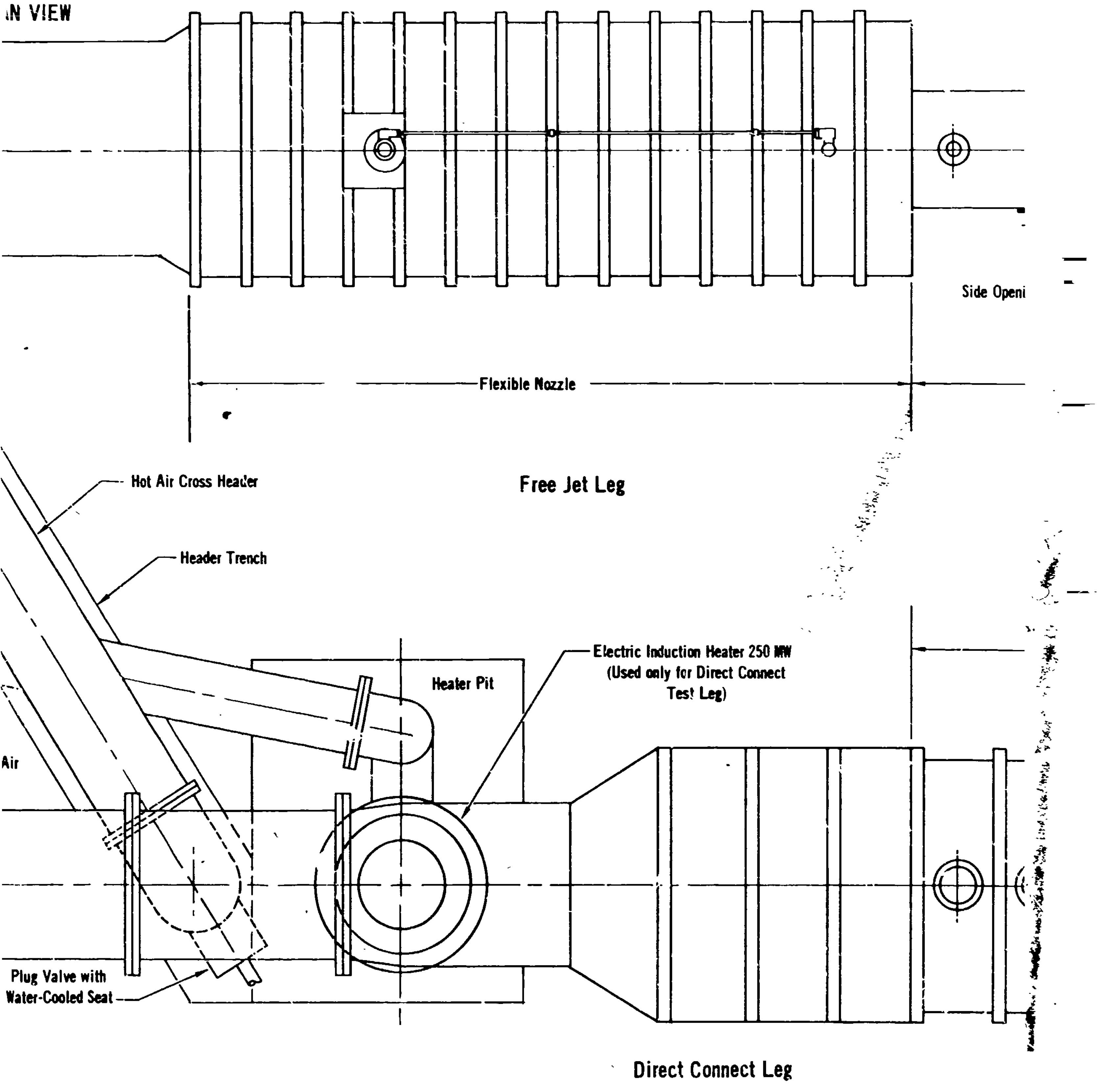

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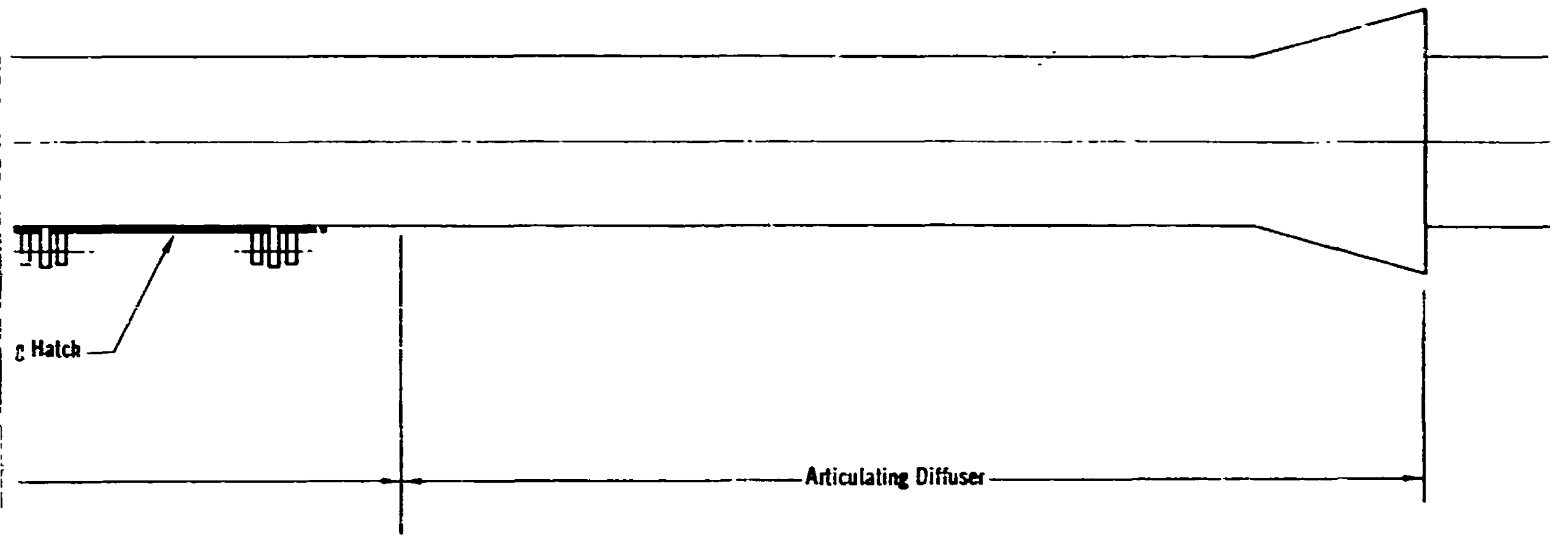

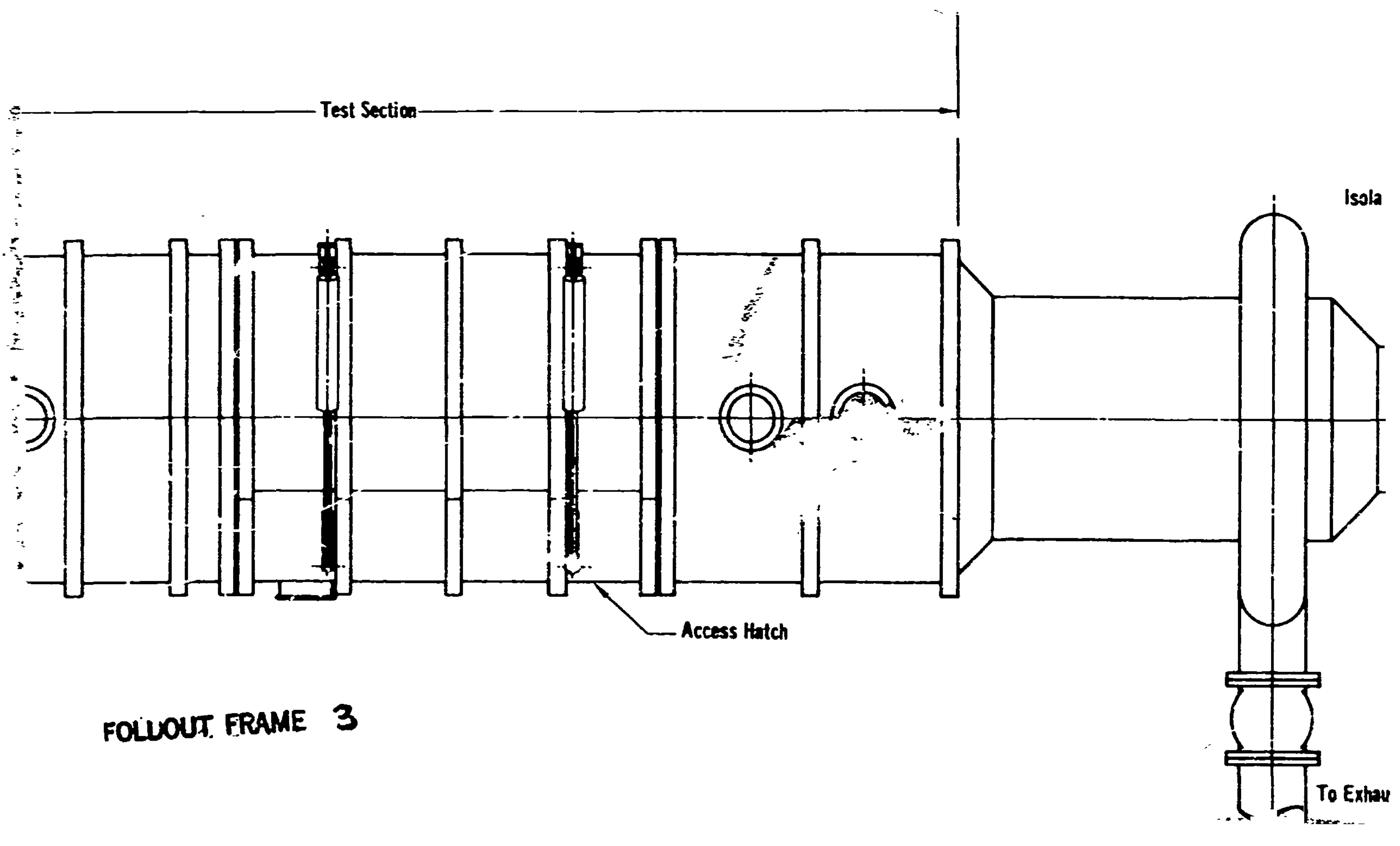

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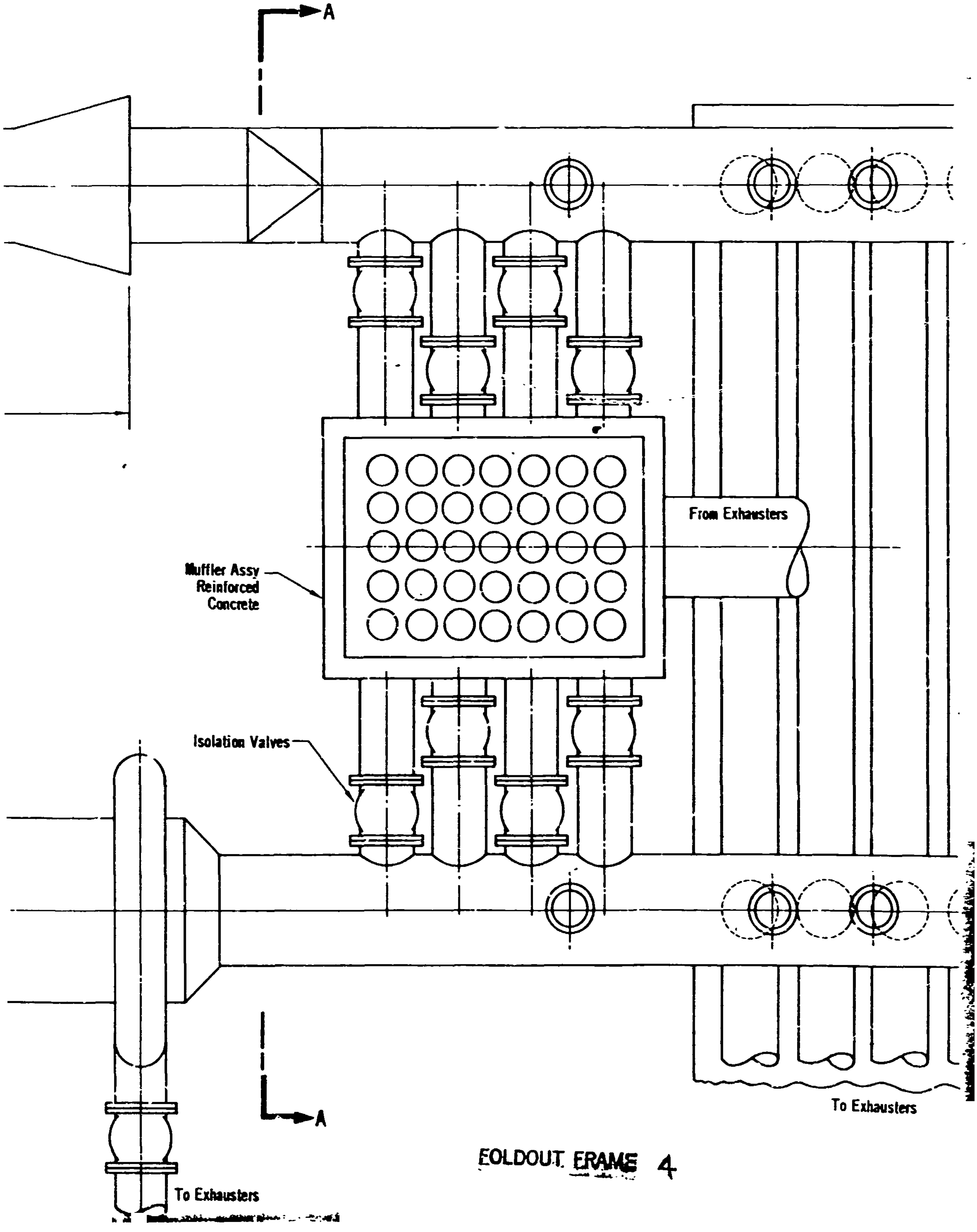

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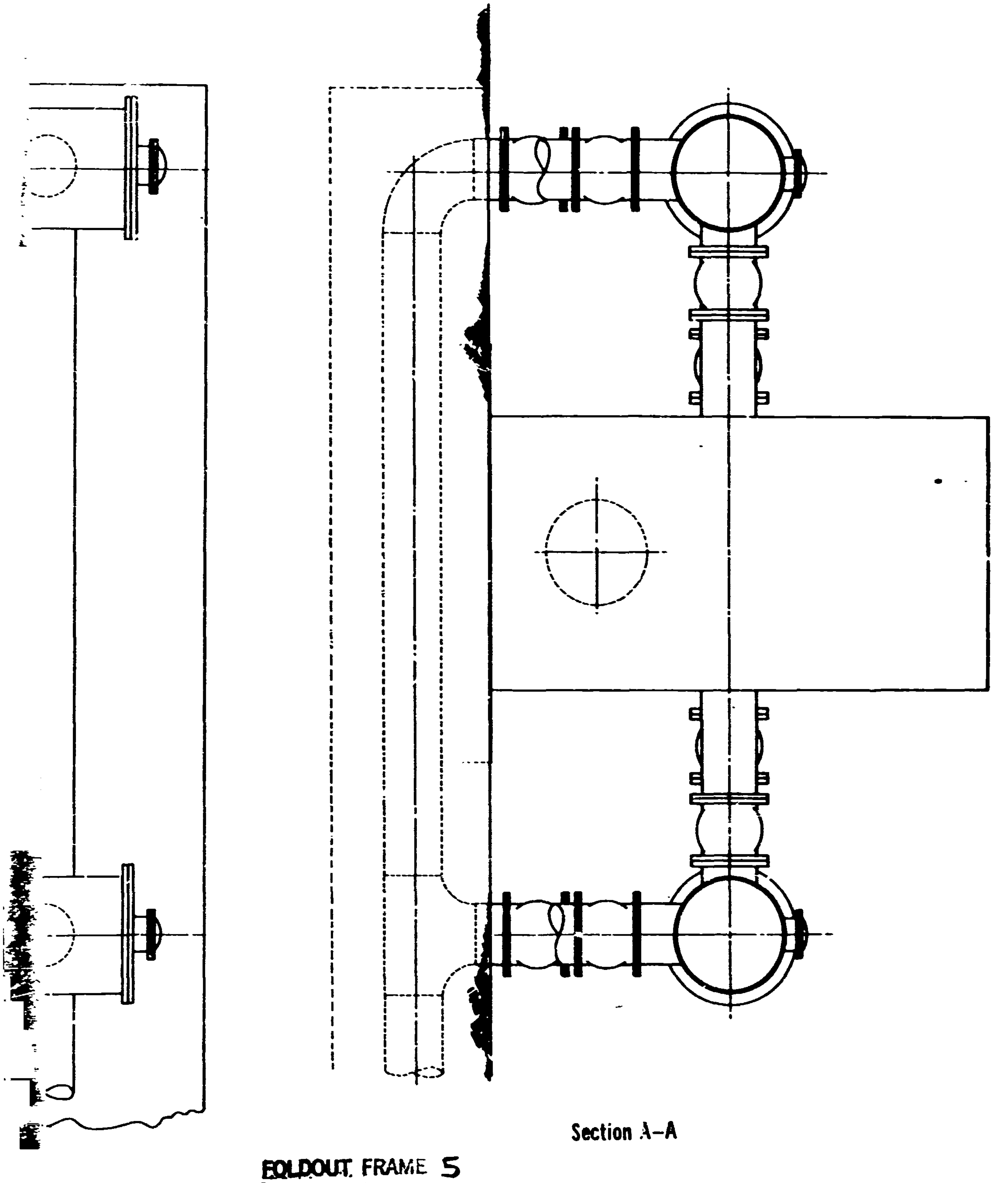

Section A–A

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A large gate valve is used to isolate the large diameter cold air piping from the test leg while the heater system is operating. This valve must be protected from the hot air by a cold air bleed downstream of the valve. Water cooling may also be required for the valve trim. A water cooled plug valve is used to isolate the direct connect leg from the free jet leg, to which it is connected by a cross header. This pipe is used to permit the use of two induction heaters in the direct connect leg when high mass flow and maximum power are required. In regards to control and safety, these valves should be interlocked into the facility control as configuration interlocks to verify their position prior to running.

The inlet piping and stilling chamber consist of large diameter sections insulated externally for refrigerated flow conditions and internally to protect the piping walls during hot flow conditions. The stilling chamber houses a flow spreader and burner. The access hatch must be interlocked to prevent operation with the hatch unsecured. In addition, emergency shutdown switches should be provided within the stilling chamber for added personnel protection.

The stilling chamber is designed to accommodate a carbon fuel burner which may be necessary if the main heater system, described in Section 6.2.5 cannot be designed to operate at 2000°F (1093°C) outlet air temperature. The carbon fuel burner consists of a piping manifold gridwork with many small burner jets. A burner control system interlocked to the facility operation will be necessary. This system must be capable of assuring proper burner operation regarding air temperature and of identifying problem situations such as blow-off which could fill the stilling chamber with a combustible mixture and be hazardous to operation. Burners of this nature have been installed in the inlets of test facilities and have been operated successfully. Design and fabrication problems are not anticipated with the burner system; however, the operation, interlocks, and control procedures will require careful study to provide a safe operating system.

The test cabin is a 20 foot (6 meter) diameter, 73 foot (22 meter) long vessel containing a replaceable inlet pressure bulkhead, a suspended thrust bedload cell arrangement which adapts to several engine stand configurations, and a downstream bulkhead containing the engine exhaust collector. The test cabin is fitted with a monorail crane to assist installation. Equipment access is provided through a large side opening hatch which opens to floor level for ease of installation. The complete interior of the test cabin shell is insulated to protect against the heat generated by the test engine.

The test cabin, as designed, features the capability of handling three types of engines up to 120-inch (3 meter) diameter and incorporating the respective inlet ducting requirements and exhaust configurations. The specific details of the three engine inlet duct configurations vary significantly and in reality will vary somewhat between engines of the same type. The important consideration is that the test cabin be designed with flexibility such that a variety of engines and duct configurations can be installed. The most complex inlet configuration will involve the modified direct connect installation. This inlet consists of an adjustable nozzle entrance utilizing a single jack nozzle block and flexible plate. Further inlet duct adjustments are provided downstream utilizing a hinged wall single jack arrangement. Support structure, thermal protection, and automatically controlled power screw jack systems will necessarily be required. The test cabin size anticipated can handle this equipment. The design and fabrication of the direct connect arrangements are of relatively standard design and, although large, do not go beyond current fabrication capability. Additional features of the test cabin would include pressure relief equipment and blowoff diaphragms, a sump to collect water which could accumulate from the exhaust spray cooling system, and a test cabin ventilator which would be used to vent the area to protect personnel and equipment against possible explosion, fire hazards or toxic fumes. Fire suppression equipment will also be necessary in and around the test cabin area. The test cabin should be fitted with safety interlocks to prevent facility or engine operation unless the equipment hatch, personnel hatch, and cabin ventilation system are secured.

A portion of engine performance testing involves determination of engine controls and dynamics such as (1) engine starting and acceleration, (2) determination of operating limits relating to combustor blowout, compressor stall, etc., and (3) determination of engine characteristics in regards to achieving stable operation and rapid response to items such as changing load demands. To safely conduct engine performance tests will require precise handling of the engine control systems in conjunction with the operation of the facility. To accomplish this, the engine must necessarily be instrumented with fast response sensors whose output can be interlocked to allow engine and facility shutdown before a potentially hazardous condition arises. Among these sensor measurements are fuel flow conditions and the temperature of various components and pressures within these components. Each sensor readout system should incorporate preset limits, which, if exceeded, would shut the facility down in normal fashion in an emergency mode, depending upon the overload condition.

It is assumed that the control room will be sufficiently removed and protected from the test area and that the area will be cleared of personnel during facility operation.

To provide static pressure simulation for turbofan engine testing, an exhauster manifold around the engine exhaust duct is provided which is sized to handle the fan flow. When testing this configuration, the fan flow exhauster must be programmed into the interlock system as a portion of the overall facility and engine control system. This system must also incorporate safety interlocks to prevent operation if either test cabin hatch is open.

The primary engine exhaust ducting is interchangeable depending upon engine configuration. This exhaust ducting utilizes backside water cooling to protect the duct inlet and water spray cooling to reduce the exhaust gas temperature before entering the muffler or exhauster. The water cooling systems, including controls, storage, and treatment, will necessarily require safety interlocks to assure proper cooling water availability and control prior to testing. If water system failure occurs during testing, an emergency shutdown operation would be initiated.

The water spray cooled engine exhaust is ducted either directly to the muffler in the case of sea level testing, or to the exhauster plant and then to the muffler in the case of altitude simulation testing. When the exhausters are used, additional cooling must be done to reduce the inlet temperature to the exhausters to 100°F (37.8°C), and to reduce the specific volume of the inlet flow to the exhausters by removing waper vapor. This job is handled by the dehumidification cooling system, which is described in Section 6.2.6.

Isolation valving is provided in both the sea level and altitude simulation exhaust configurations. The exhaust ducting is fitted with pressure relief and blowoff systems in the event of over pressurization. Access to the exhaust ducting will be necessary to accomplish inspection and routine maintenance. The access hatch and interior of the exhaust ducting must be fitted with interlocks and safety switches to prevent operation with the hatch open. The isolation valving between the exhaust duct and muffler, and between the exhaust duct and exhausters will require interlocks to verify the ducting configuration prior to running.

The muffler is common between the two test legs of this facility and also handles the flow from the exhauster plant. The basic configuration utilized here is identical to that of the gas dynamics facilities. The muffler attenuates low frequency noise utilizing a perforated section and high frequency noise in tubular exhaust stacks lined with acoustical treatment material. The basic muffler structure is reinforced concrete. Safety precautions to prevent injury to personnel while inspecting or maintaining the muffler will be required.

A major design challenge of the facility will be in the area of establishing an operating procedure or process control which identifies the operating sequence required for safe operation, such that the specific facility subsystem interlocks and engine test condition interlocks can be specified and incorporated into the various components.

There are no features of this test leg which represent any major requirements for development programs or research, with the possible exception of the design of the direct-connect bellmouths and the modified direct-connect apparatus. The large size of valves and test leg components, compared to existing facilities, necessitates assignment of a confidence level of 4 to the test leg. The cost of the direct-connect test leg is estimated to be $9,959,000.

6.2.2 FREE JET TEST LEG - This test leg is used to provide flow to an operating engine/inlet combination, on a continuous basis, at actual flight Mach numbers up to 5.0. The test section is 8 feet (2.4 m) high by 4.5 feet (1.4 m) wide. It can accommodate approximately half scale versions of the largest advanced technology inlet/engine packages.

Mechanical and structural details of the free jet test leg are shown in Figure 6-6 and 6-5, while Figure 6-1 presents an isometric view of the entire facility, showing the relationship of the two test legs to the support systems.

The test leg is connected by a complex system of piping and valving to a compressor/exhauster plant, a heater system, a cooling system, an intake tower and an exhaust muffler. All systems operate on a continuous basis and can be varied through the entire Mach number, altitude range while running.

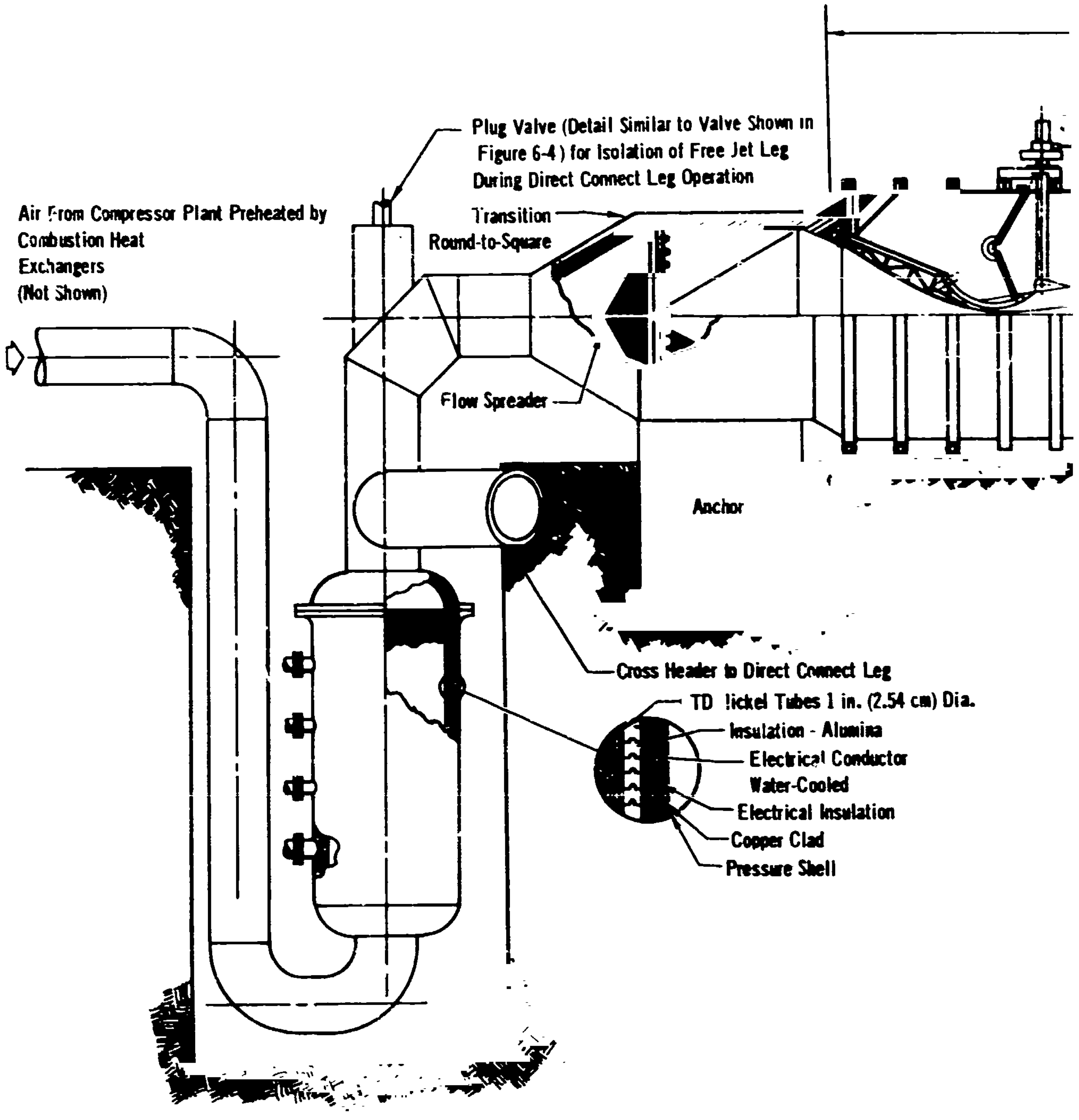
The stilling chamber is an internally insulated piping section containing the flow spreader and, if required, a carbon fuel burner similar to that described for the direct connect test leg. In this test leg, the stilling chamber is the anchor point, and the downstream sections of the test leg are supported on trackage which allows for longitudinal expansion and alignment. Access to the stilling chamber will be required for flow spreader, burner and adjustable nozzle inlet inspection and maintenance. This access hatch and the interior of the stilling chamber should include interlock switches to prevent operation and to shutdown facility operation.

A water cooled single jack nozzle, with an adjustable nozzle block and a flexible plate is used to provide free stream conditions to the test section. This nozzle is similar in design concept to that used in a supersonic wind tunnel at the FFA facilities in Sweden (Reference 5), the primary difference being size. This nozzle is approximately five times larger and must withstand three times the temperature and two times the pressure loads of the Swedish design. The adjustable throat components are designed such that the loads on these components are nearly balanced, allowing adjustment during a run with moderate power required to drive the screw-jack. The flexible plate portion completes the nozzle contour. Minor adjustments are available at the downstream end to provide for boundary layer compensation. This compensation mechanism operates off the nozzle block screw jack system. The temperature requirements of the test leg require that sections of the adjustable nozzle be water cooled which complicates the design problem. The adjustable nozzle walls seal against water cooled sidewalls which are structurally supported within the 20-foot diameter pressure shell. The design problems associated with this nozzle will fall within the details of the adjustment mechanism. This system is power driven and must be interlocked into the facility control system to assure a proper positioning program during test leg operation and synchronization of both sides of the nozzle.

A seal arrangement must be provided at the nozzle block pivot in the stilling chamber. Leakage in this seal could pressurize the pressure vessel behind the nozzle. To prevent damage if leakage occurs, the vessel should be fitted with pressure relief and blowoff safety equipment. Pressure sensors should be installed to detect leaks and initiate facility shutdown procedures. The water cooling system for the nozzle and sidewalls must be interlocked to the facility control operation to assure proper cooling conditions prior to the start of a run. During a run, the water system conditions must be automatically monitored and interlocked into an emergency shutdown procedure should the water cooling flow or pressure become inadequate. Access for inspection and maintenance of critical nozzle areas such as seals, adjustment mechanisms, and water connections should be provided. These access areas will require safety switches within the shell and interlocked hatches to prevent operation or to shut down the facility.

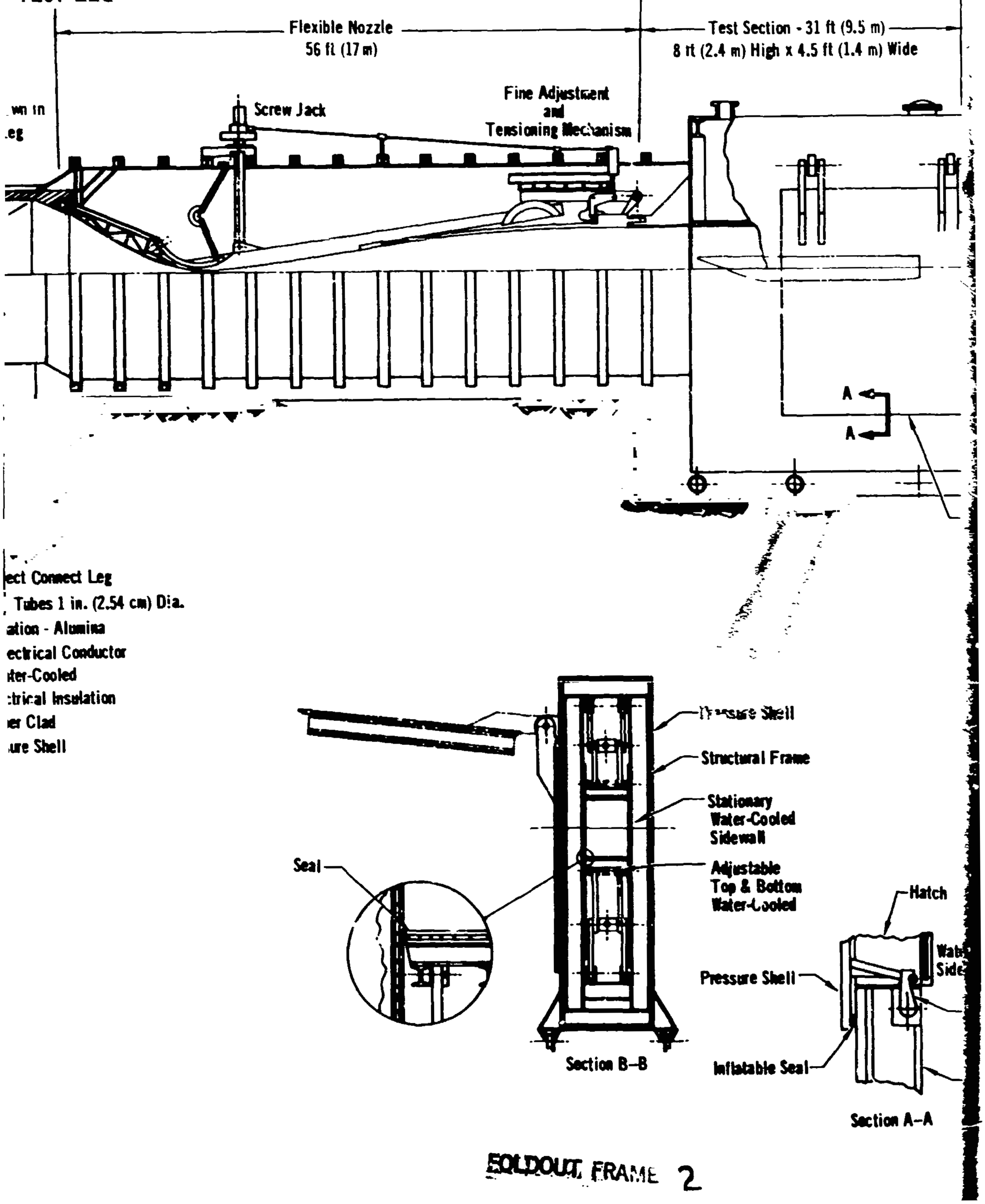
The articulating test section, which provides a thrust stand and support for the full scale operating engine, is capable of movement to allow engine angles of attack between -6 to +22°. The test section and adjustable diffuser are actuated together to provide a suitable diffuser ducting configuration. The details of the two extremes of test section and diffuser articulation are shown on Figure 6-6 The articulated test section and diffuser is the design concept which allows the nozzle height to be only 8 ft (2.4 m) and still allow pitching the inlet/engine combination to 22°. If a standard propulsion wind tunnel approach is used, where the test section is large enough to pitch the test article, test section height of about 20 ft (6.1 m) is required. The articulated test section and diffuser is specified in order to minimize facility construction costs and facility support system requirements. No major cost saving can be made without some sacrifice however. In this application, although full duplication of inlet Mach number is

FIGURE 6–6
E20 TURBOMACHINERY TEST FACILITY – FREE JET TEST LEG



FOLDOUT FRAME 1

TEST LEG



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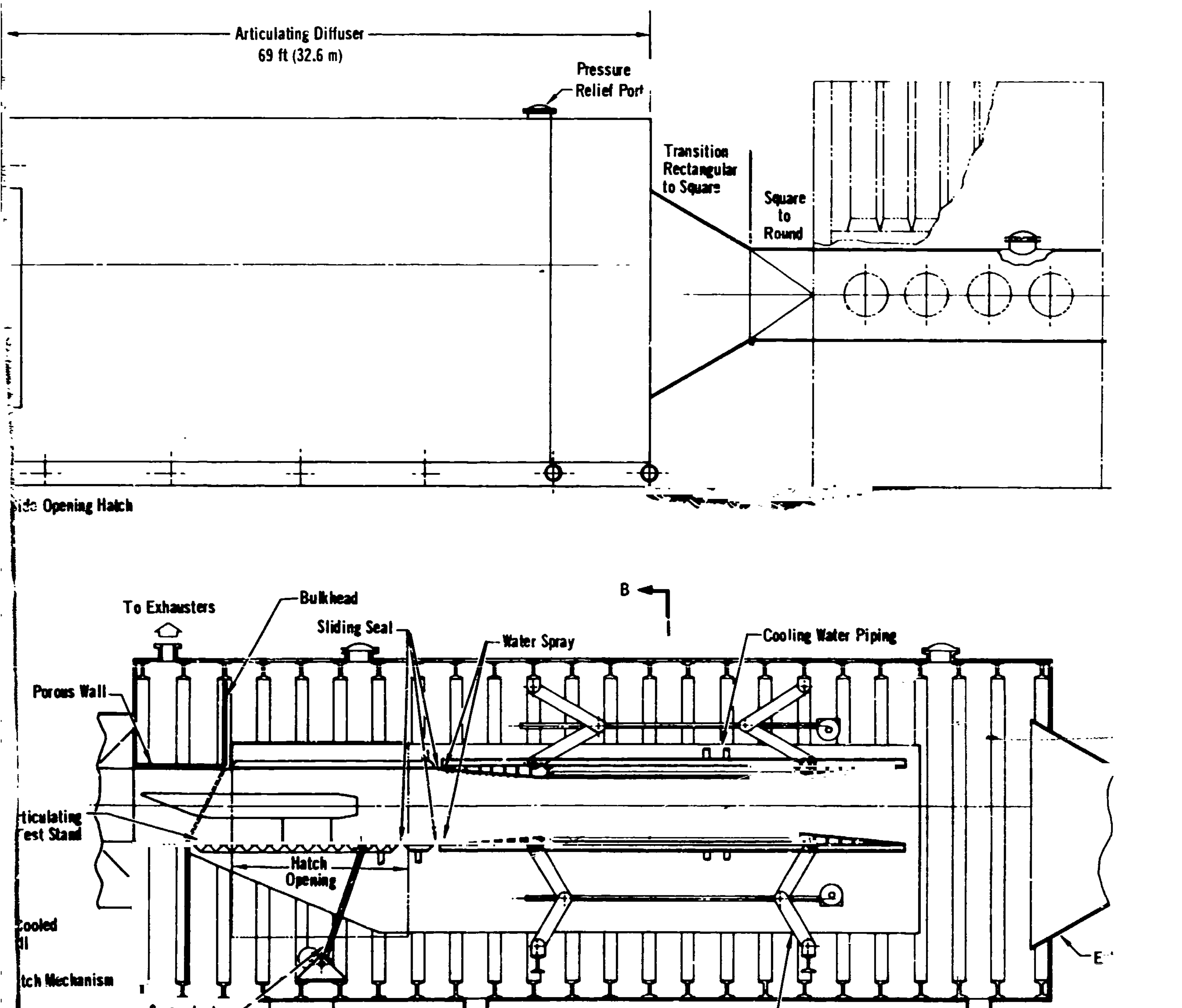

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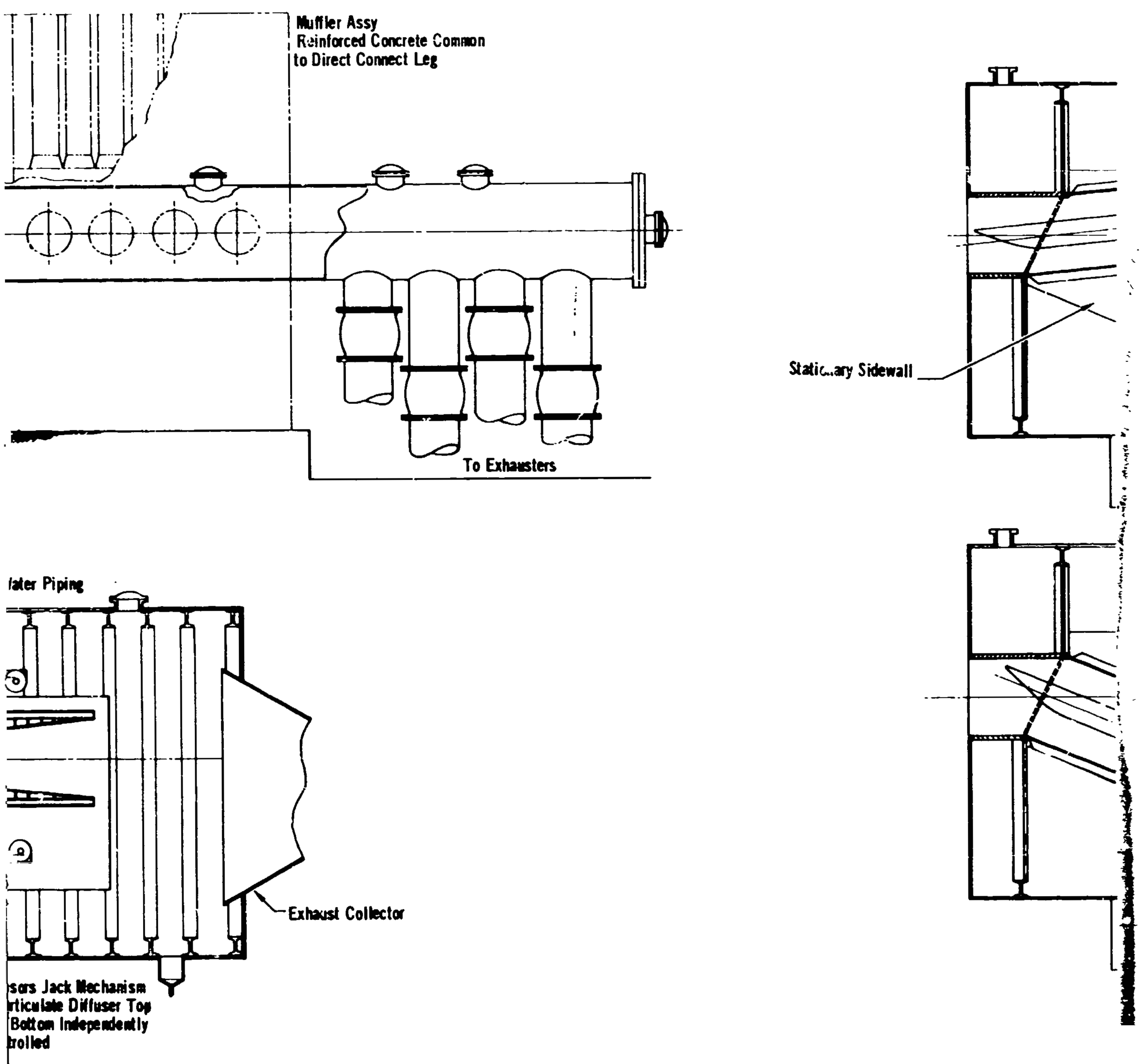

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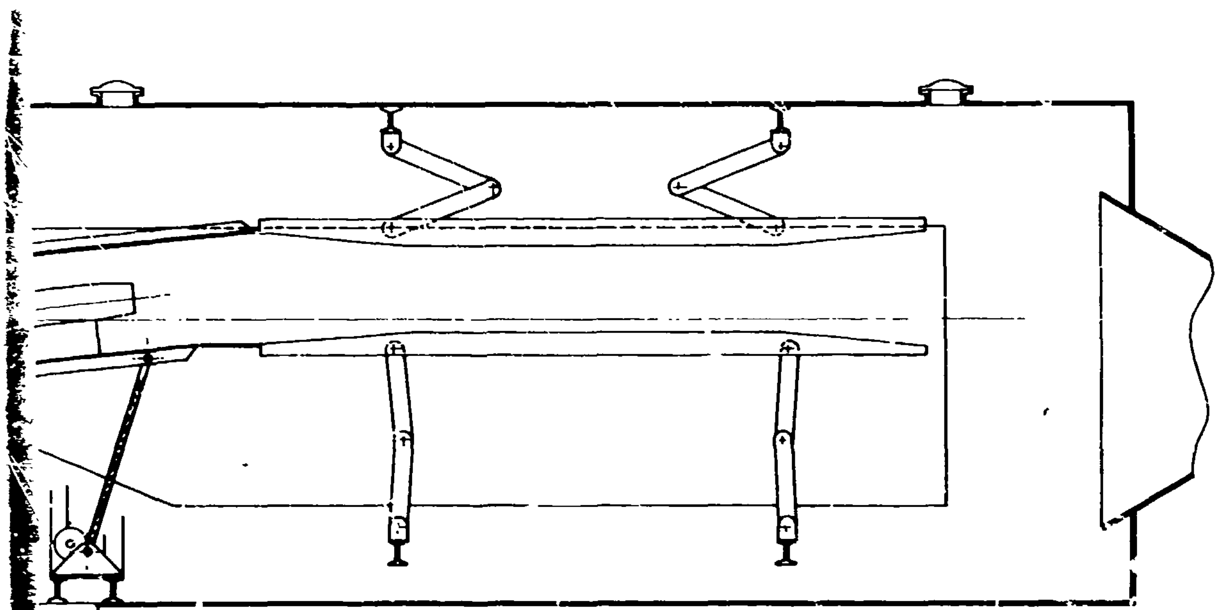
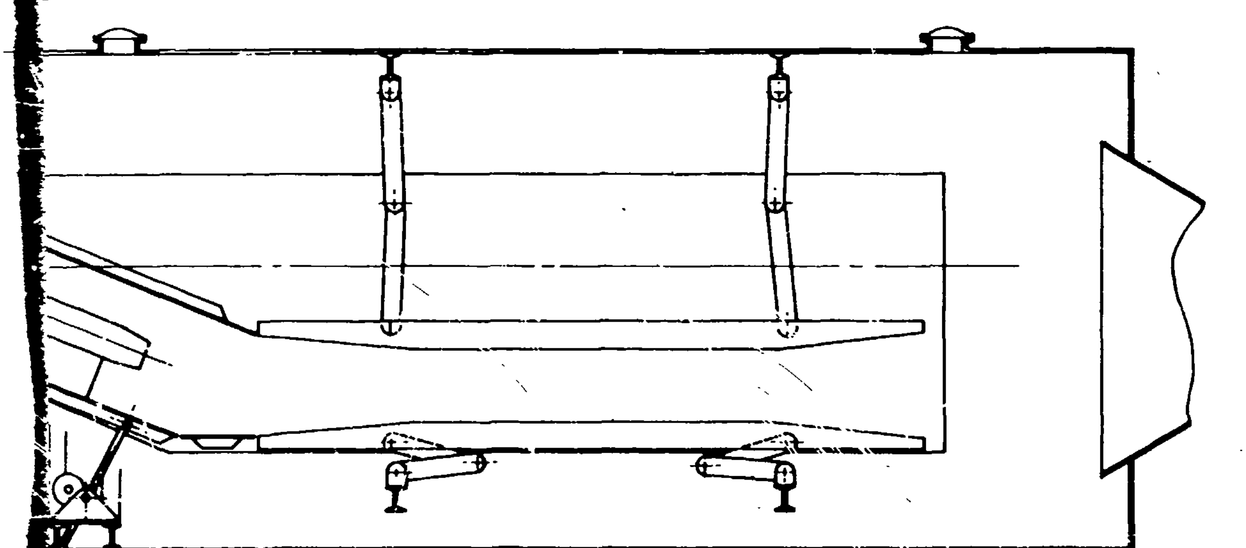


Articulated Test Stand at
Minimum Angle of Attack −6°



Articulated Test Stand at
Maximum Angle of Attack +22°

FOLDOUT FRAME 5

attained, the facility flow field near the engine exhaust is compromised because of the shock waves and expansion fans which emanate from the upstream pivot points of the test section when it is pitched. It is felt, however, that although this may affect thrust measurement, that dynamic interactions of the inlet and engine will be accurately reproduced. Shock waves emanating from the inlet nose are cancelled by the perforated test section ceiling, through which an auxiliary suction system operates.

The diffuser is hinged to the downstream end of the test section and is articulated so that it maintains a horizontal position as it slides up and down within the water-cooled sidewalls. Differential motion of the top and bottom surfaces of the diffuser allow optimized diffuser throat settings for all test section Mach numbers. This feature is required to allow maximum pressure recovery in the exhaust ducting, which minimizes exhauster inlet flow volume. The positioning systems to articulate the test section and diffuser and the hinged and sliding seal sections will provide a formidable design problem.

Continuous facility and engine operation over a range of conditions with test section variations will require a complex control and safety interlock system to assure a safe, properly sequenced, and coordinated operation. Some of the hardware and subsystem items in the test cabin-diffuser arrangement which will require interlocking to the test leg control system are:

o Water cooling to sidewalls and diffuser spray in proper condition for running. After run is started, the water system is interlocked such that failure of the system would automatically shut down the facility.

o The facility air flow control and compressor plant operation must be preprogrammed to the adjustable nozzle and the articulating test section-diffuser sequenced with both. If a real time trajectory is considered, the timing of the sequence operation will necessarily complicate the control and interlock system.

o The engine control will require sequencing to the test conditions and adjustable nozzle configuration. After run start, adjustments of the nozzle, to change test conditions, will probably necessarily be slow. Avoiding pressure and temperature fluctuations may be critical to the engine performance, and care to avoid off-design loading will be necessary.

o Sensors measuring engine conditions and the conditions of the many components of the test leg will be interlocked to avoid excessive loads from developing and to initiate shutdown should they arise.

The structure housing the test section and diffuser is a rectangular beam structure which supports the sidewalls and articulating mechanism for the moveable top and bottom sections. A large equipment hatch is provided to allow engine installation. This section must also be fitted with pressure relief and blow-off equipment. To remove excess spray water which is not vaporized, a sump is provided in the bottom of the structure. An additional feature which must be included within the test cabin area is a ventilator which vents the area to protect personnel and equipment against possible explosion, fire hazard, or toxic fumes. Fire suppression equipment must be provided in and around the test section while

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the cabin is open and work is being performed on the test article. The hatch and ventilation system must be interlocked to prevent operation unless secured.

At the downstream end of the diffuser, a transition section from rectangular to square to round collects the exhaust and directs the flow into the muffler or exhauster piping. The transition inlet is sized to handle the exhaust with the diffuser at either extreme of articulation.

Depending upon the test conditions, the exhaust flow is either carried directly to the muffler or the exhausters. The discharge from the exhausters also enters the muffler system. Isolation valves in the muffler and exhauster lines provide control over the exhaust test configuration. These valves must be interlocked to assure the proper exhaust configuration prior to starting to run.

The muffler system was previously described in the discussion of the direct connect test leg and will not be repeated. The muffler structure is common to both the direct-connect and free jet test legs.

The free jet leg, although not extremely large, incorporates features which have not been incorporated in existing engine test facilities. Design details and verification of the operating principles of the water-cooled nozzle and the articulated test section and diffuser should be worked out on a small scale before a commitment to final design is made. Because of these factors, a confidence level of 2 is assigned to the free jet test leg. The cost of the test leg is $4,879,000.

6.2.3 COMPRESSOR/EXHAUSTER PLANT - The mass flow requirement at altitude and Mach number for each of the assumed engines and the free jet leg was translated into facility inlet and exhaust conditions.

For the inlet side, which must be provided either straight from atmosphere or by a compressor plant, the mass flow and inlet pressure were converted to compressor inlet volume flow rate and pressure ratio (Pr) so as to determine total compressor requirements. Inlet volume flow was calculated at an inlet pressure of 13.8 psia (9.5 N/cm^2) to allow for inlet pressure drop, and at an inlet temperature of 90°F (32.2°C). Relative humidity at these conditions was assumed to be 50%. Required pressure ratio was calculated by:

$$Pr = P_2/P_1 = P_2/13.8$$

where P_2 was determined from the total pressure required at the test leg stilling chamber plus frictional pressure losses produced by the supply line and the stilling chamber hardware.

The results of these calculations are presented graphically in Figure 6-7a, which portrays the minimum pressure and volume flow requirements.

Similar calculations were made for total exhauster requirements. In this case, Pr is defined as before, but P_1 is the variable inlet pressure and P_2 is constant, defined to be 14.7 psia (10.1 N/cm^2). Inlet temperature was assumed to be 100°F (37.8°C). Since moisture is introduced into the flow by both the combustion in the engine and by the spray cooling apparatus, the relative humidity of the flow entering the exhausters is 100% at all inlet pressures. This water vapor must be considered when calculating inlet volume flow because at a Pr = 9 (P_i = 1.63 psia (1.12 N/cm^2) for example, saturated flow at 100°F (37.8°C) has a total volume 2.4 times the dry air volume. Another factor included in the total volume flow was the contribution added by the engine fuel. This was taken to be six percent for hydrogen and 3% for JP fuel. Exhauster inlet pressure, which is used to calculate both Pr and volumetric flow rate, was assumed to be 70% of normal shock recovery.

With the above assumptions, the total exhauster requirements were calculated and are shown in Figure 6-7b.

Analysis of the compressor plus exhauster requirements at any given test condition showed that at the maximum compressor volumetric flow rates, exhauster requirements were minimal and sometimes non-existent (direct exhaust to atmosphere). The reverse situation was also true. By providing four independent banks of machines, all four of which can be operated as exhausters, and three of which also be operated as compressors, all the simultaneous compressor/exhauster requirements of the facility can be satisfied. These four banks each have a nominal inlet flow of 1,000,000 cfm (28,320 m^3/min). The characteristics of the individual banks are shown in Figures 6-7c, d, and e.

Allis Chalmers has developed the specifications for a compressor/exhauster plant which will fulfill the requirements as developed. A schematic of this plant and a bill of material is shown in Figure 6-8. Banks 1 and 2 are identical and satisfy the requirements presented in Figure 6-7c. For the flows requiring Pr's equal to or less than 11, two VA-1800 machines are in series with 4 V-1300 machines. When a Pr greater than 11 is needed, one of the V-1300 machines is put in series with the other 3 V-1300 machines creating, in effect, a third stage with overall Pr = 31. To do this job, the odd V-1300 machine is powered with a 60,000 hp (44,700 kW) motor rather than the 22,500 hp (16,750 kW) supplied on the other three machines. Bank 3 is used primarily as an exhauster, but does come into use as a compressor when total compressor requirements exceed 2,000,000 cfm (56,600 m^3/min). This bank does not require the fourth machine in the second stage. Bank 4 is used only as an exhauster and consists of two VA-1800 machines in series with a single VA-1400 machine. A total of 20 compressors are required for the plant. This compressor/exhauster plant is a very sophisticated plant in that it can be configured to perform various combinations of compressor/exhauster and operate over a wide range of pressure ratio and flow. The cost of this plant is broken down as follows:

Mechanical components: Including all equipment listed on the bill of material plus installation and set up charges.		$ 99,541,000
Machine footings, foundation and building.		2,600,000
	Total	$102,141,000

Although one of the largest single compressor plants designed, all components represent hardware either available or designed, so a confidence level of 4.5 is assigned.

FIGURE 6-7
CHARACTERISTICS OF E20 COMPRESSOR/EXHAUSTER PLANT

a. Total Requirements When Operating as Compressor (Banks 1, 2, and 3)

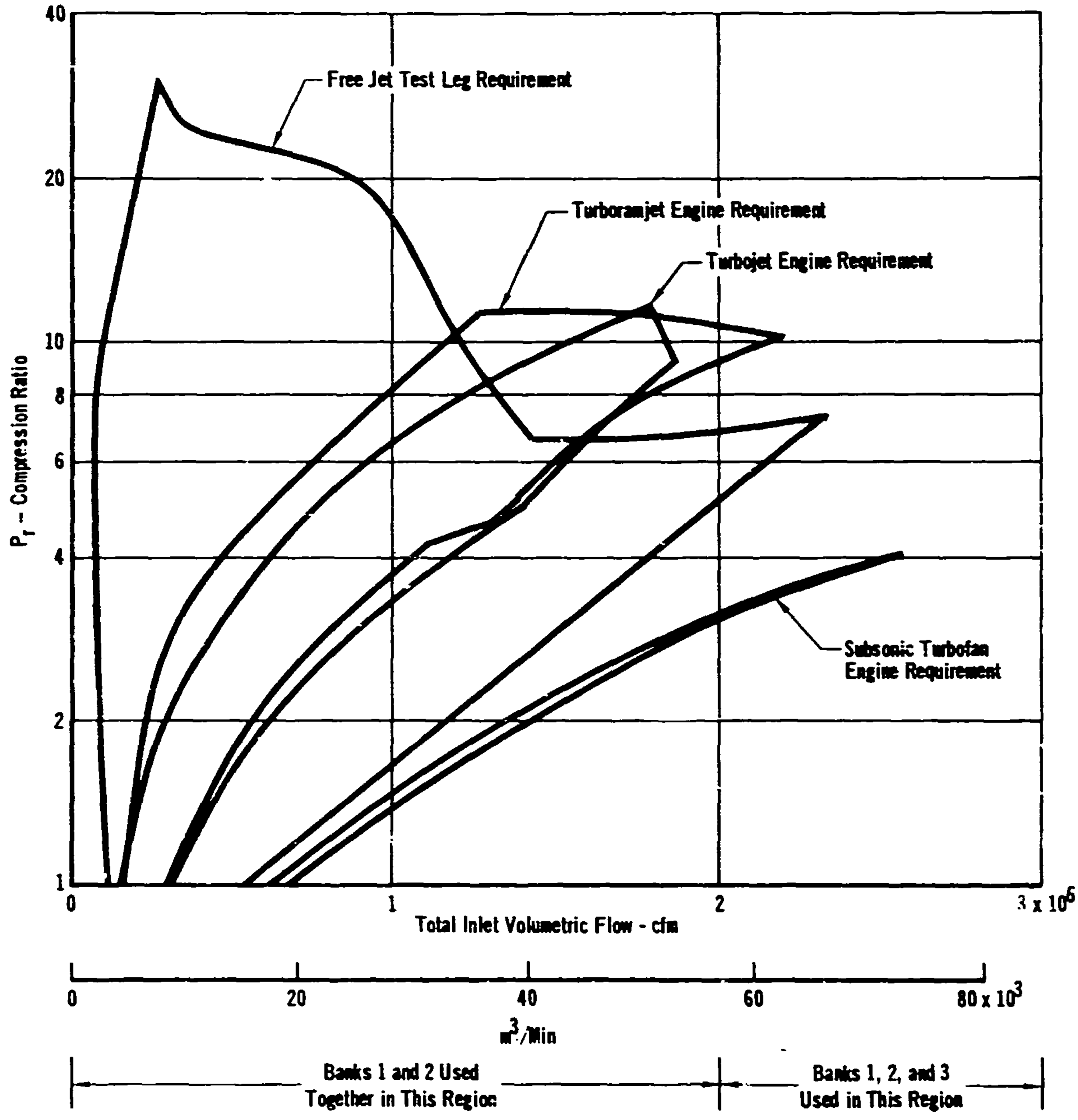


FIGURE 6-7 (Continued)
CHARACTERISTICS OF E20 COMPRESSOR/EXHAUSTER PLANT

b. Total Requirements When Operating as Exhauster (Banks 1, 2, 3, and 4)

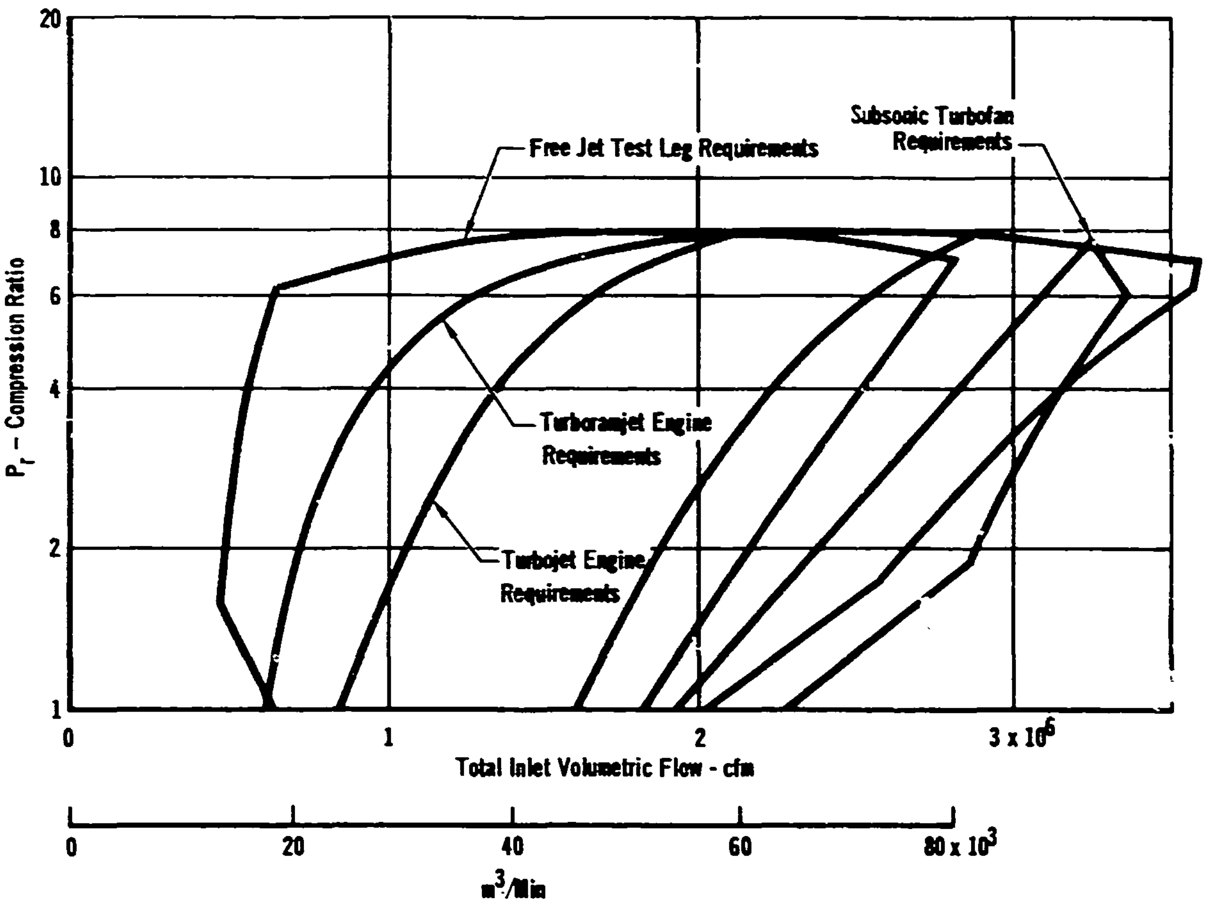


FIGURE 6-7 (Continued)
CHARACTERISTICS OF E20 COMPRESSOR/EXHAUSTER PLANT

c. Individual Requirements of Banks 1 and 2

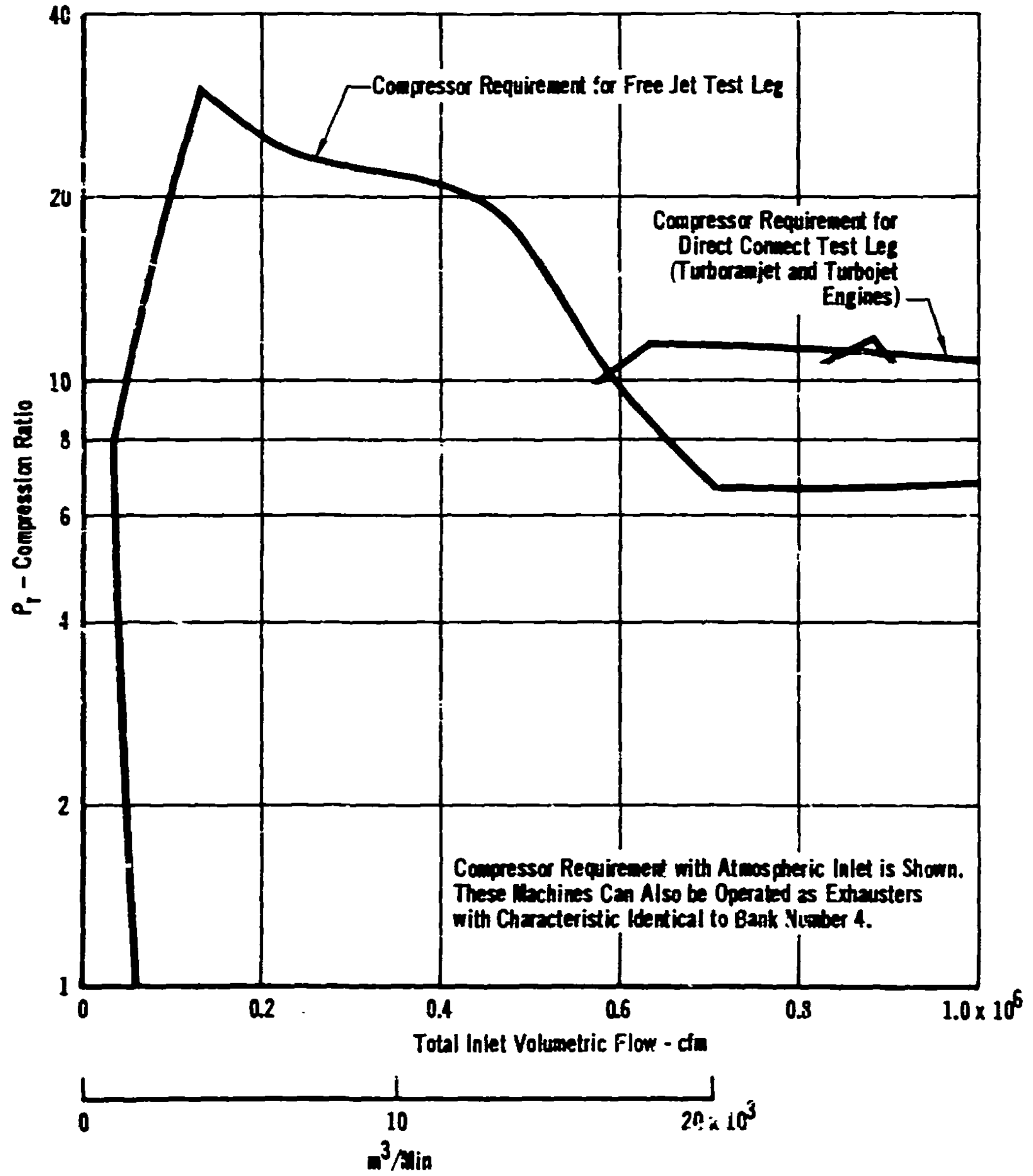


FIGURE 6-7 (Continued)
CHARACTERISTICS OF E20 COMPRESSOR/EXHAUSTER PLANT

d. Individual Requirements of Bank 3

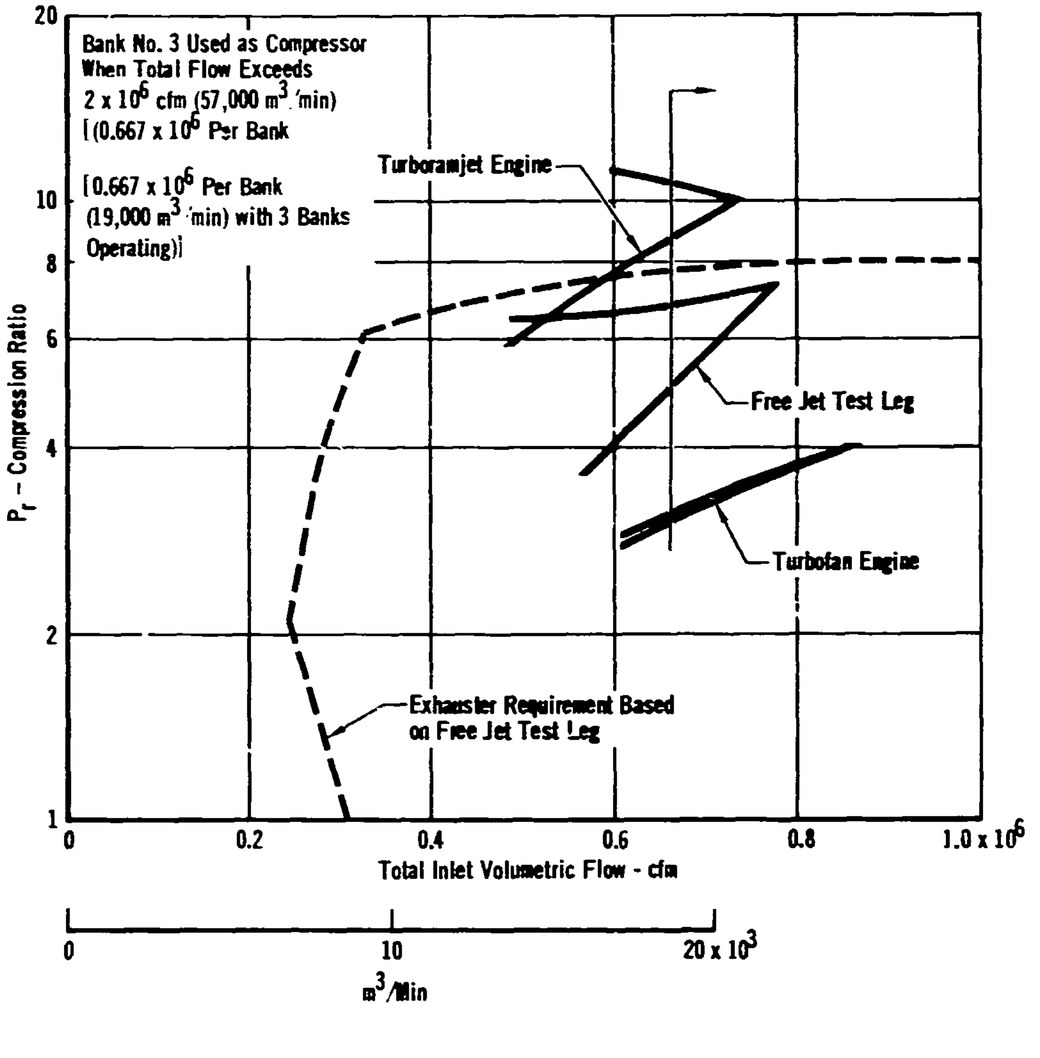


FIGURE 6–7 (Continued)
CHARACTERISTICS OF E20 COMPRESSOR/EXHAUSTER PLANT

e. Individual Requirements of Bank 4

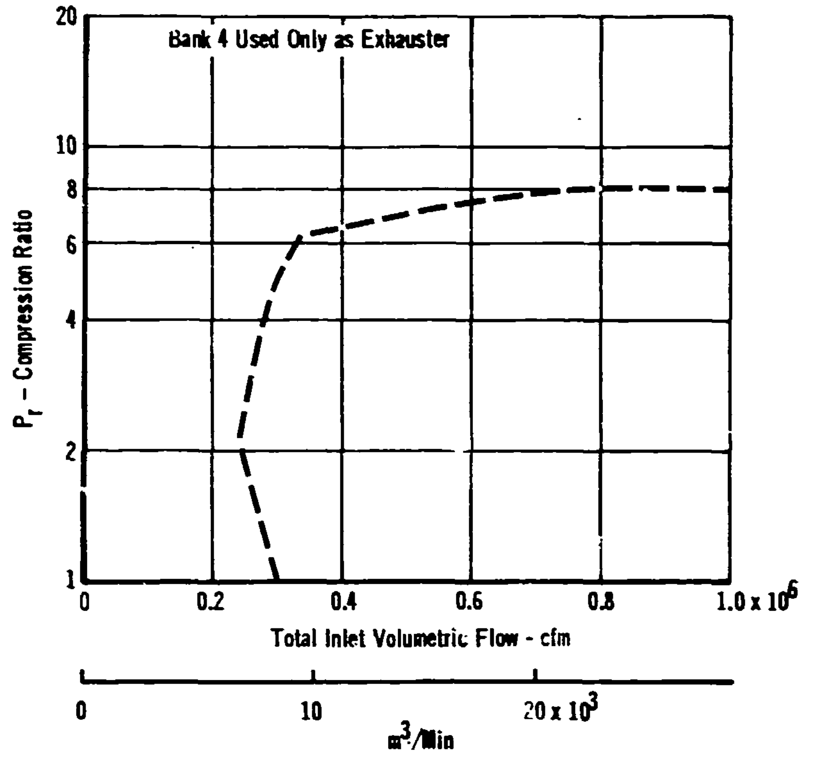
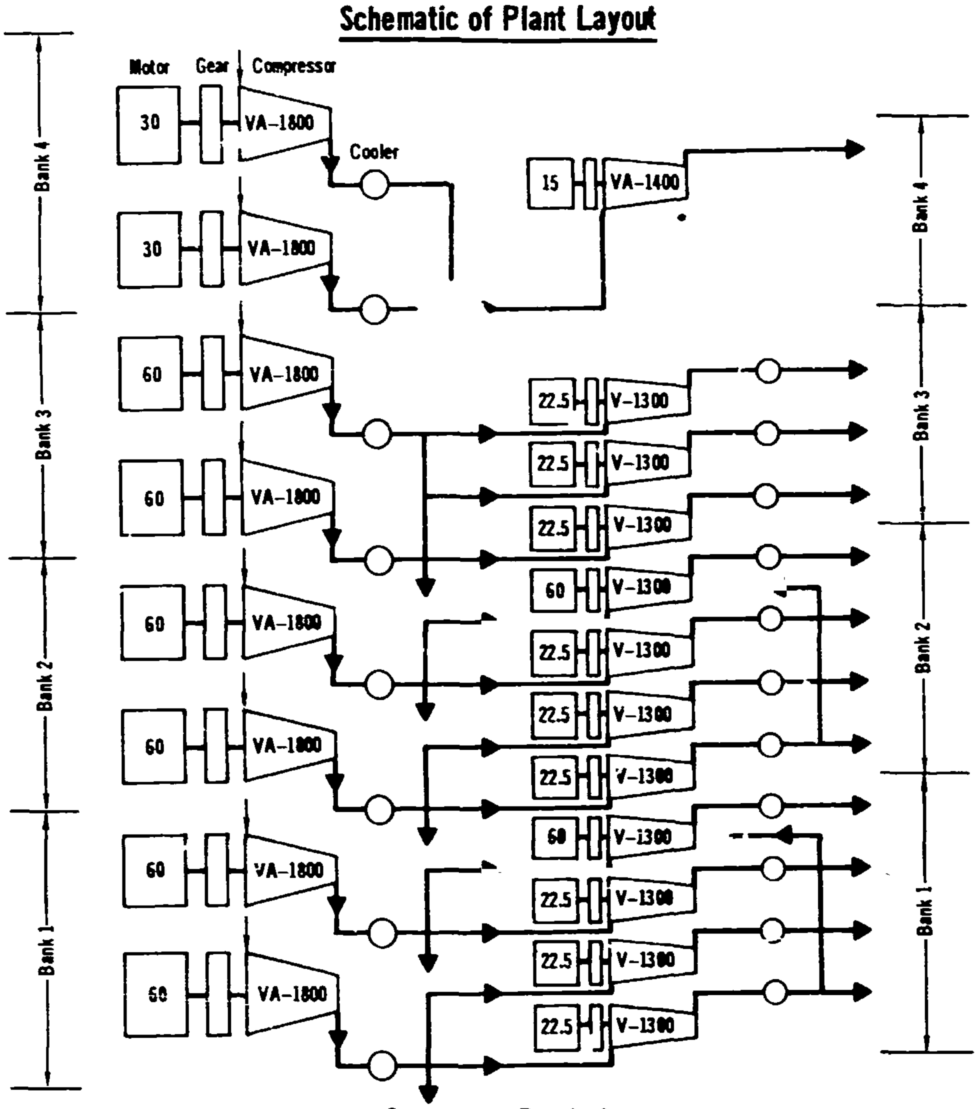


FIGURE 6-8
E20 COMPRESSOR/EXHAUST PLANT

Schematic of Plant Layout



Compressors Required

	First Stage		2nd Stage	Parallel – 2nd Series 3rd	2nd Stage
Type Compressor*	VA-1800	VA-1800	V-1300	V-1300	VA-1400
Inlet Volume - cfm (m^3 min)	500,000 (11,600)	500,000 (11,600)	62,500 (1770)	62,500 (1770)	250,000 (7100)
Pressure Ratio	4.0	2.9	2.8	2.8	3.9
Power – hp (kW)	60,000 (45,000)	30,000 (22,500)	22,500 (16,800)	60,000 (45,000)	15,000 (11,250)
Used on Bank	1,2,3	4	1,2,3	1,2	4
Total Used	6	2	9	2	1

*Allis Chalmers Model Numbers

Utilities Summary

Total Compressor Power	- hp (kW)	757,500	(563,000)
Cooling Water Requirements	- gpm (m^3 min)	190,000	(720)
Water System Power	- hp (kW)	41,000	(30,500)
Hydraulic System Power	- hp (kW)	5,000	(3,720)
Total Power	- hp (kW)	803,500	(597,220)

Bill of Material

Compressors	Switch Gear	Dryers
Motors	Control Center	Water Pumps
Sole Plates	Transformers	Cooling Tower
Lube Systems	Anti-Surge Control	Compressor
Coolers	Interconnecting Piping	Evacuation System
Gears	and Valving	

6.2.4 COMBUSTION HEAT EXHANGERS - The original intent regarding inlet flow heaters for this facility was that electrical induction heaters would be used. However, initial inquiries regarding the cost of induction coils revealed that this item alone would cost about $245 million when a separate and adequate induction heater was specified for each test leg. Two changes were made in order to reduce heater cost. First, it was decided to share total heater capacity between both test legs. Second, it was decided to use combustion fired air-to-air heat exhangers, which are relatively inexpensive to acquire and operate, to do the initial heating as high as 1000°F (538°C).

The total heat exchanger requirements for the turbojet engine, the turboramjet engine and the free jet test leg are shown in Figure 6-9. Fifty percent heat exchange efficiency is assumed and inlet temperature, from heat-of-compression, is 300°F (149°C). The shaded area represents the chosen temperature and heat input boundaries. Two independent units are used, each having the following rating:

Max Heat Transfer.	1 x 10^9 Btu/hr	(1.05 x 10^{12} Joules/hr)
Inlet Temperature.	300°F	(149°C)
Max Outlet Temperature	1000°F	(538°C)
Max Mass Flow.	1140 lbm/sec	(517 kg/sec)
Max Pressure	400 psia	(276 N/cm^2)

Estimated cost of the combustion heat exchanger units is $20 million. These units, although very large, will probably be assembled using multiple units of current design, and are thus given a confidence level of 4.5.

6.2.5 INDUCTION HEATERS - A pair of continuous duty electric induction heaters with total input power of 500 MW are used to provide temperatures from 1000° to 2000°F (538° to 1093°C). The total heating requirements for the turbojet engine, the turboramjet engine, and the free jet test leg are shown in Figure 6-10. The chosen heater temperature and power limits are indicated. A portion of the turboramjet envelope will not have true temperature duplication because of the power limitation chosen. This area, though large in the To, $\dot{w}$ plane (Figure 6-3b), represents only a small region of high Mach number, low altitude testing which is not available with the flight duplicated stagnation temperature, and affects only the turboramjet engine as defined (Figure 6- 2). Twice the proposed induction heater capacity would have to be provided, at an additional cost of approximately $83 million, in order to completely cover the requirements of the TRJ engine. It is felt that the limitation of total heater power to 500 MW was a reasonable trade-off of test capability versus component cost. The 250 MW modular approach taken, however, permits the incremental addition of more units if that capability is needed.

This type of heater is not common in current operations; however, induction heaters have long been utilized as research tools and for industrial applications. This particular heater is not the storage type but must run continuously, an added design consideration. It should be noted that it will be necessary to consider additional study on a small scale prototype basis to assure that satisfactory

FIGURE 6-9
E20 COMBUSTION HEAT EXCHANGER REQUIREMENTS AND LIMITS

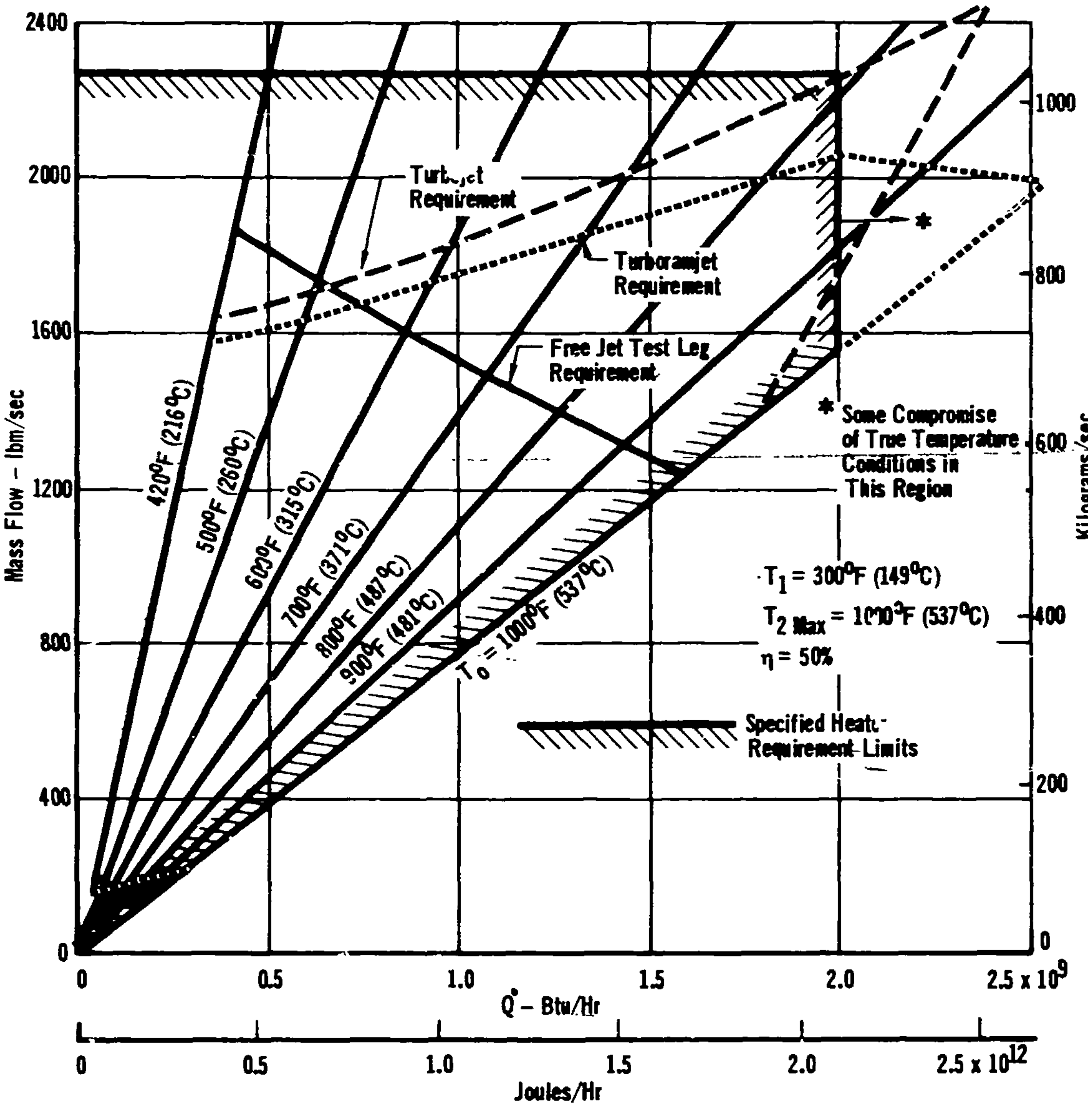
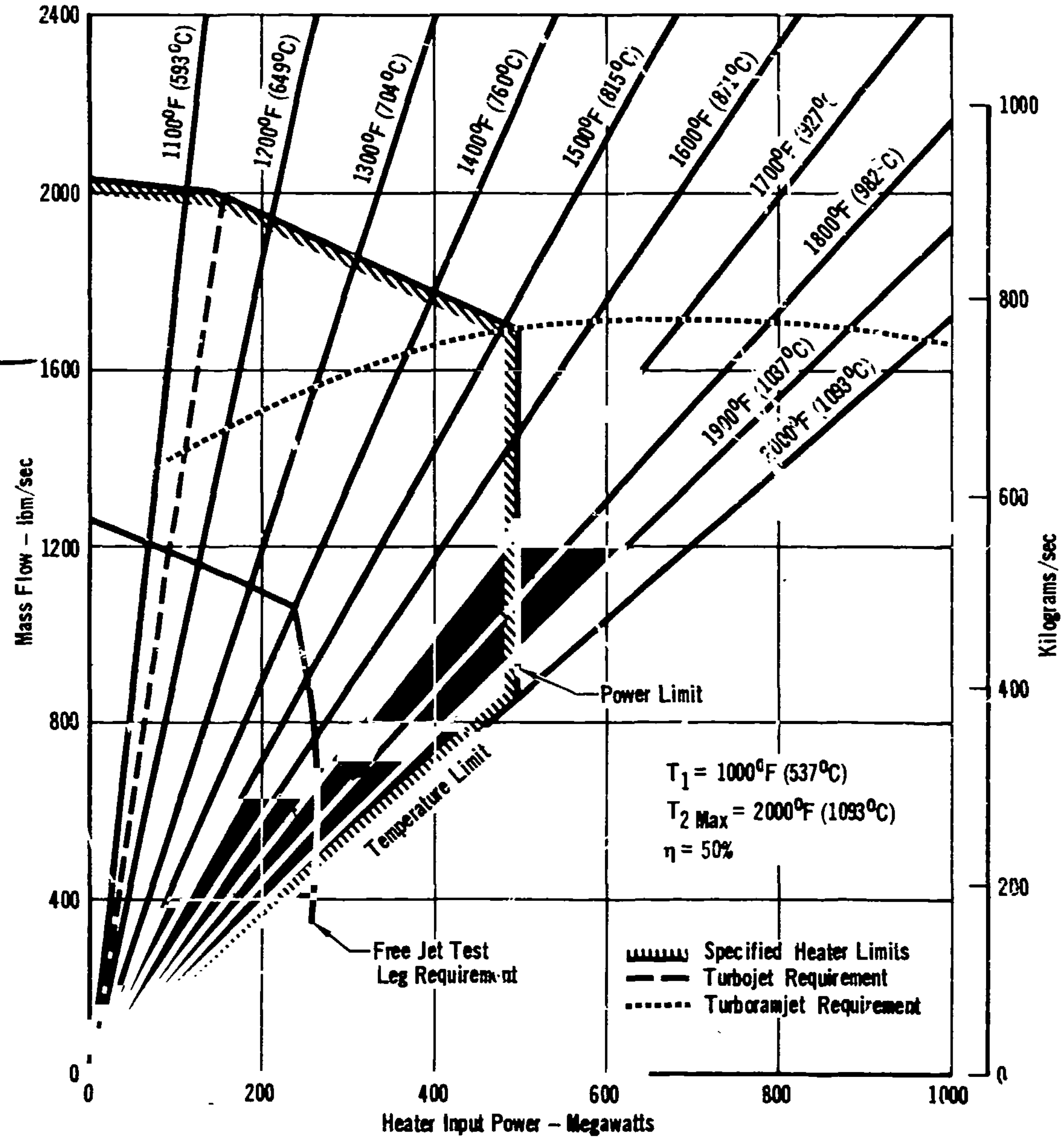


FIGURE 6–10
E20 ELECTRIC INDUCTION HEATER REQUIREMENTS AND LIMITS



heater operations under the operating conditions of this facility will be obtained in the ultimate design.

Each heater is suspended in a pit and is supported on columns which allow heater expansion without a change in the horizontal centerline. The airflow enters the bottom of the heater and is discharged, hot, into the stilling chamber piping. This allows the grate to be designed for temperature conditions less severe than the matrix. An added design feature could be incorporated to provide air cooling to the grate structure which could eliminate the grate as a possible limitation on the heater operation.

The continuous electric heater consists of a matrix of T.D. nickel or columbium tubes, supported on a grate structure at the bottom of the vessel, heated by electrical induction. Water cooled electric coils, insulated from the tube matrix by alumina brick, provide the heat generating field. Several coil circuits are provided to allow flexibility in the heating process. The heater must incorporate temperature sensing instrumentation in the matrix, insulation, and on the vessel, which is interlocked into the facility operation.

The electrical coils are water cooled. This cooling water system will require special treatment to prevent corrosion and degradation of the copper coils. The water system must be adequately instrumented and controls interlocked to allow facility shutdown in the event of heater system failure or coil failure. The cooling water pressure must be balanced with the heater air pressure. The design and fabrication challenges anticipated with respect to this heater fall within the electrical heating system, i.e., the electric power control system, the electric coils, the terminal connection which penetrates the vessel and the electric coil support and insulation within the heater.

Each induction heater is rated as follows:

Maximum Power	250 Megawatts	
Inlet Temperature	1000°F	(538°C)
Maximum Outlet Temperature.	2000°F	(1093°C)
Maximum Mass Flow	1020 lbm/sec	(465 kg/sec)
Maximum Shell Pressure.	400 psia	(270 N/cm^2)

These induction heaters probably represent the greatest technical risk area among all the major support systems. As previously mentioned, it is possible that materials, reliability, or operational difficulties may restrict the performance of these heaters and alternate heater types, or supplemental heaters like the carbon fueled burner may have to be provided. The estimated cost of the induction heater system, including its gas turbine generator power supply is $107,456,000. A confidence level of 2 is assigned.

6.2.6 <u>SPRAY COOLING AND DEHUMIDIFICATION COOLING SYSTEM</u> - The heat introduced into the air flow by the inlet heaters and the engine operating in the test section must be removed so that the exhauster inlet volume flow is reduced to a minimum and that flow temperature is low enough for reliable operation of the downstream configuration valving and exhauster machinery.

A water spray, located directly behind the test section in both test legs, is used to drop the flow temperature from temperatures in the 4000° to 5000°F (2200 to 2700°C) range to about 100 to 210°F (37.8 to 100°C). The actual temperature downstream of the spray is a unique function of the pressure at that location, since the flow then contains fully saturated vapor. Likewise, the amount of water required per pound of dry air is a unique function of the static pressure, for a given upstream air temperature. These fractions are shown in Figure 6-11a for an upstream air temperature of 4000°F (2480°C) and an initial water temperature of 80°F (26.7°C). The minimum downstream temperature under these conditions is also shown as a function of static pressure. If excess water is sprayed in, no additional cooling will be obtained, the excess being drained to the barometric well. With the range of air flows available in E20, a spray system having a water flow rate of 20,000 gpm (75.6 m^3/min) is required.

The maximum allowable compressor inlet temperature is 100°F (37.8°C). An air-to-water heat exchange system is installed downstream of the spray cooling unit to obtain this final increment of cooling. As the temperature of the wet air mixture drops in the cooler, nearly all of the water vapor introduced by the spray cooler is condensed out of the flow, greatly reducing the volume flow to the exhausters. The relationships for this process are shown in Figure 6-11b. The heat exchangers, known as dehumidification coolers, are built in eight individual units, one on each exhauster bank inlet pipe. These coolers are each 33 ft (10 m) in diameter and approximately 50 ft (15 m) long. Each group of two coolers is serviced by a water supply system which brings 80°F (26.7°C) water from a lake or reservoir and returns the warm water to the reservoir. A third cooling system is provided for the backside cooling of the throat area of the free jet nozzle. This system is a closed-loop demineralized water system, incorporating a water-to-water heat exchanger. Chilled water for the heat exchanger is provided by reservoir water.

A brief summary of the three cooling systems follows:

Spray Cooling:

Maximum Flow Rate.	20,000 gpm	(75.6 m^3/min)
Maximum Pressure	50 psi	(34.5 N/cm^2)
Pump Horsepower.	1,040 hp	(775 kW)
Cost.	$498,000	

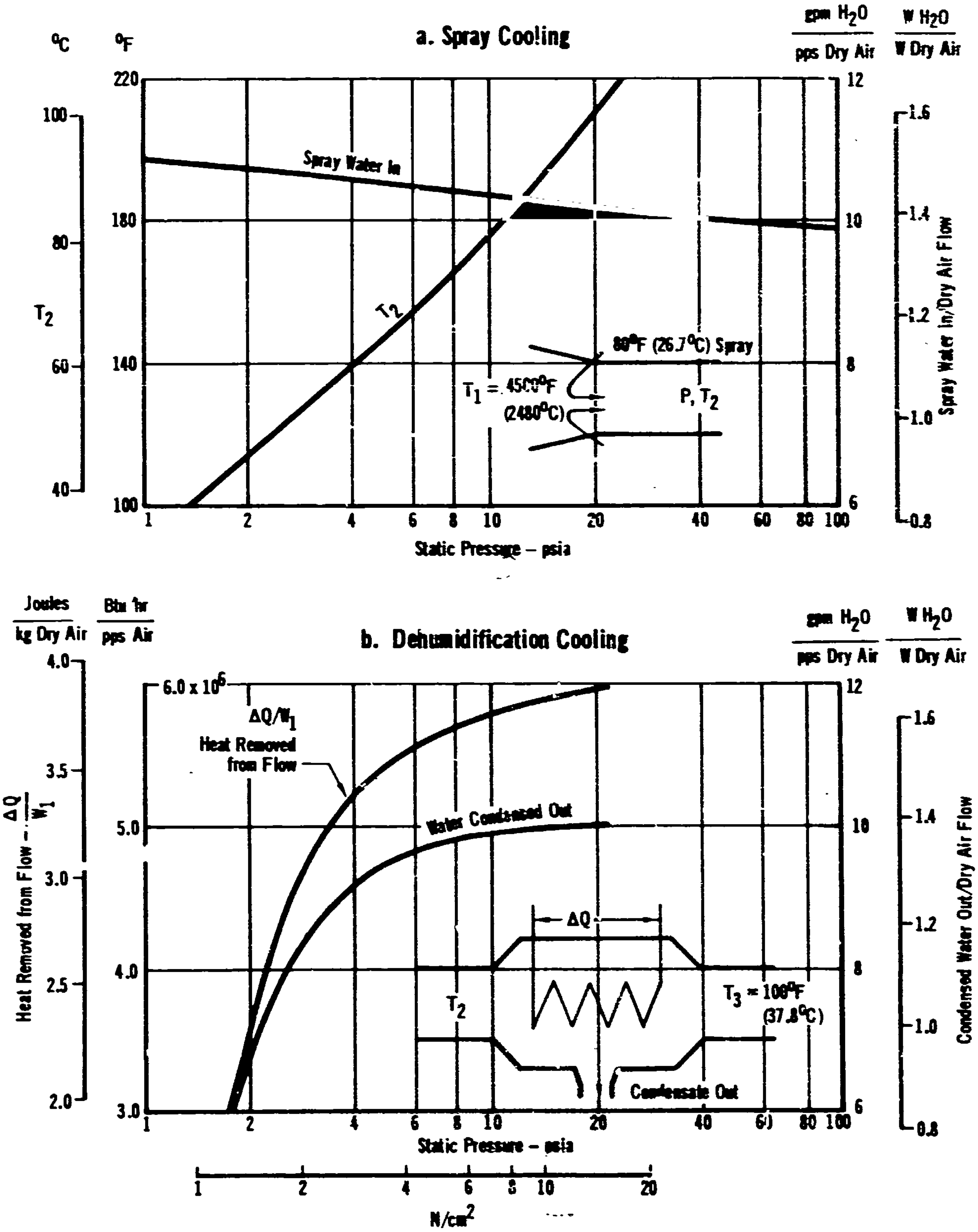
Dehumidification Coolers:

Heat Exchangers - 8 Finned Tube Type Units, Each

33 ft dia x 50 ft lg

Maximum Flow Inlet Temperature	210°F	(99°C)

FIGURE 6-11
E20 FLOW COOLING RELATIONS



Outlet Temperature (All Conditions)	100°F	(37.8°C)
Maximum Total Dry Air Flow Rate	2,000 lbm/sec	(910 kg/sec)
Maximum Total Wet Mixture Flow Rate	4,830 lbm/sec	(2190 kg/sec)
Maximum Heat Exchange Requirements	12×10^9 Btu/hr	(12×10^{12} Joules/hr)
Total Water Flow Requirements (Provided in Four Separate Systems)	690,000 gpm	(2610 m^3/min)
Maximum System Pressure	90 psia	(62 N/cm^2)
Total Water Pump Power	68,800 hp	(51,200 kW)
Cost	$23,900,000	

<u>Nozzle Water Cooling:</u>

Demineralized Water System

Flow Rate	600 gpm	(2.3 m^3/min)
Maximum Pressure	210 psia	(145 N/cm^2)
Minimum Water Temperature	80°F	(26.7°C)
Maximum Water Temperature	207°F	(97.2°C)
Water Pump Power	150 hp	(112 kW)

Water to Water Heat Exchanger

Maximum Heat Exchange Required	39×10^6 Btu/hr	(41×10^9 Joules/hr)
Reservoir Water Flow	9,750 gpm	(37 m^3/min)
Maximum Water Pressure	130 psia	(90 N/cm^2)
Water Pump Power	1,200 hp	(900 kW)
Cost	$430,000	

The total water cooling requirements, though large, require the application of large quantities of industrial sized equipment, and do not require the development of new techniques. A sophisticated water flow and pressure control system closely integrated with the air flow conditions is required. A confidence level of 4 is assigned to the cooling systems.

6.2.7 <u>REFRIGERATION PLANT</u> - Simulation of the higher altitudes at subsonic and transonic Mach numbers requires the provision of refrigeration plant capacity for the inlet flow.

Refrigeration requirements were calculated for the direct-connect test leg and the results are shown in Figure 6- 12. Refrigeration capacity which is needed for the turbojet engines, the turboramjet, and the subsonic fan jet is shown. The chosen plant limits are indicated. No compromise with needed capacity has been made except for minimum air temperature, which is set at -30°F (-34.4°C) rather than the desired -60°F (-51.1°C) to elminate the need for a cryogenic system.

The given refrigeration requirements were used by Vilter Manufacturing Company to estimate the plant equipment needed, using a conventional ammonia mechanical refrigeration system.

Maximum Refrigeration Capacity. . . . . .20,800 tons (26.4 x 10^9 Joules/hr)

Maximum Air Flow. . . . . .2,580 lbm/sec(1170 kg/sec)

Minimum Air Temperature . . . .-30°F (-34.4°C)

Total Installed Power . . . . .19,950 hp (14,800 kW)

Cost. $28,303,000

It can be seen from Figure 6-12 that the major requirement for refrigeration capacity results from inclusion of the subsonic turbofan, a non-HYFAC engine. As mentioned before, this engine was included for completeness. If, however, this engine is eliminated from consideration, total plant capacity required is reduced to 7,000 tons (8.9 x 10^9 Joules/hr) for an approximate cost reduction of $19 million.

All equipment required for provision of the refrigeration capacity is similar to existing designs but is of a plant size much greater than current practice. For this reason, a confidence factor of 4 is assigned.

6.2.8 COST SUMMARY - Figure 6-13 presents a breakdown of the estimated acquisition costs. A pie chart is presented showing the relative cost of facility major components and systems (Figure 6-14).

It is shown that, for continuous operating high temperature flow facilities, the cost of providing the large air flows at the proper pressure and temperature, and then cooling it sufficiently for discharge through mechanical exhausters far exceeds the cost of the actual test apparatus. This fact gives rise to the possibility, discussed later, of constructing this facility on a modular basis. The test leg or legs would be sized as they are shown, for the large engines of the future, while all mechanical components, such as compressors, exhausters, coolers, refrigeration plant can be sized for more near term engines for initial acquisitions. The increased capacities required in the future could then be spread out over a period of years.

The operating costs were calculated according to the methods of Section 2.3.2. The following assumptions were used:

U_F = power utilization factor = .25

U_R = run utilization factor = .4

U_F = facility utilization factor = .6

N_S = staff directly charging to facility = 100

Annual Maintenance Cost $3,200,000

Using these factors results in the following breakdown of operating cost per facility occupancy hour.

Utility Provided Power	$550
Self-Generated Power	350
Fuel Costs (Oil-fired Heaters)	200
Total Energy	$1100
Staff	3300
Maintenance	2600
	$7000

FIGURE 6–12
E20 REFRIGERATION PLANT REQUIREMENTS AND LIMITS

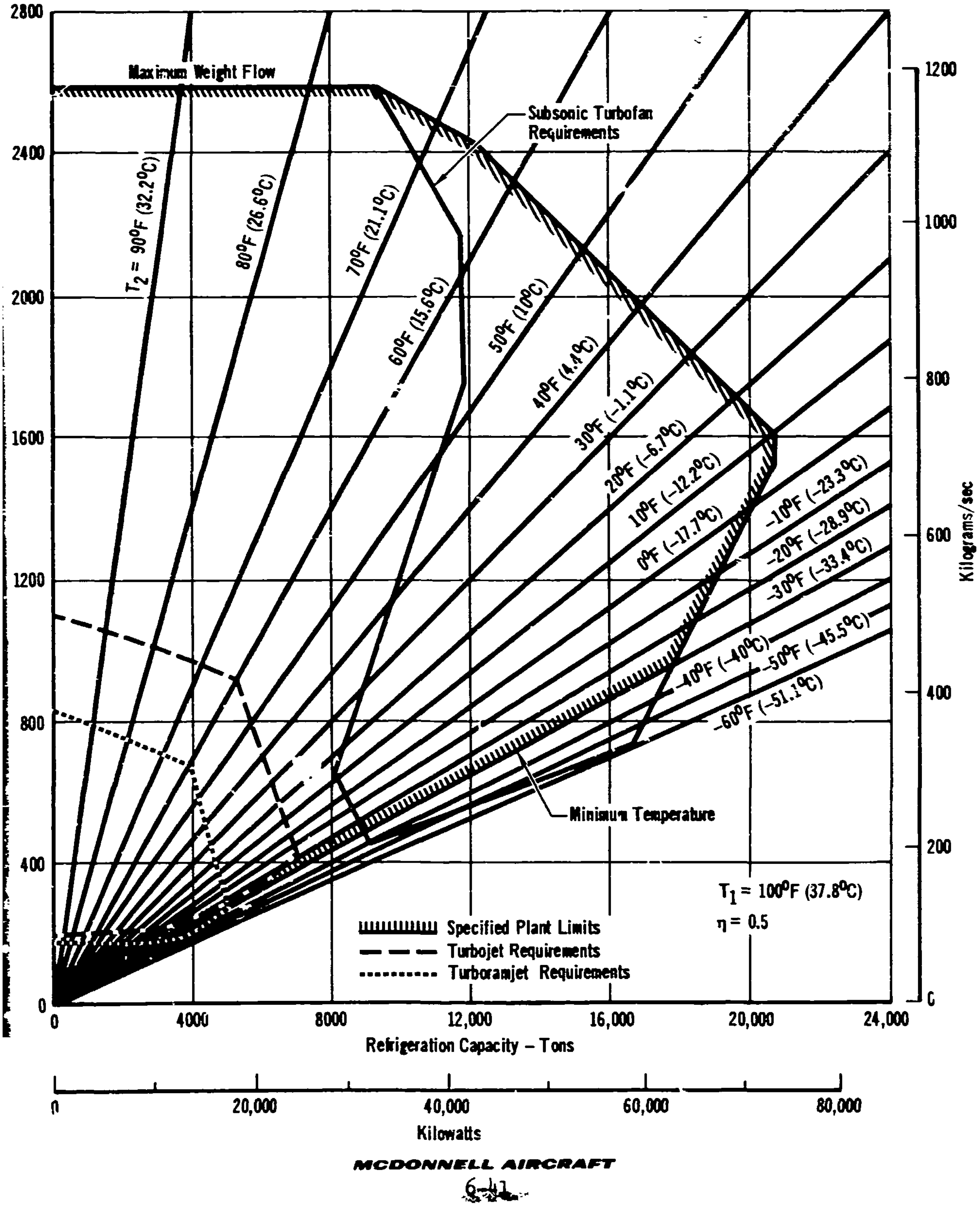


FIGURE 6-13
COST SUMMARY – E20

Facility Component	Cost ($1000's)
Test Leg, Direct Connect	
Footings and foundations	475
Pressure shell (Incl Carbon Fuel Burner)	3,627
Flow spreader	1,956
Turboramjet test nozzle	1,564
Turbojet test nozzle	1,000
Turbofan test nozzle	846
Thrust stand	105
Barometric sump	160
Diffuser	85
Water spray assembly	141
Subtotal Test Leg, Direct Connect	9,959
Test Leg, Freejet	
Footings and foundations	550
Pressure shell (Incl Carbon Fuel Burner)	2,298
Flow spreader	1,138
Flexible plate nozzle	334
Articulated test stand	114
Barometric sump	200
Porous walls	53
Adjustable diffuser and mechanism	192
Subtotal Test Leg, Freejet	4,879
Muffler	230
Induction Heater (High Pressure)	
Cold air pipe	1
Heater shell and foundation	107
Shaded pole structure	108
Induction coils	20,800
Thermal insulation	1,580
Heater tubes (Refractory Metal)	6,770
Hot air pipe	1
Control valve	2
Gas Turbine-generator packages (6-GE MS-7000 series)	18,000
Development cost	6,060
Subtotal Induction Heater (High Pressure)	53,425

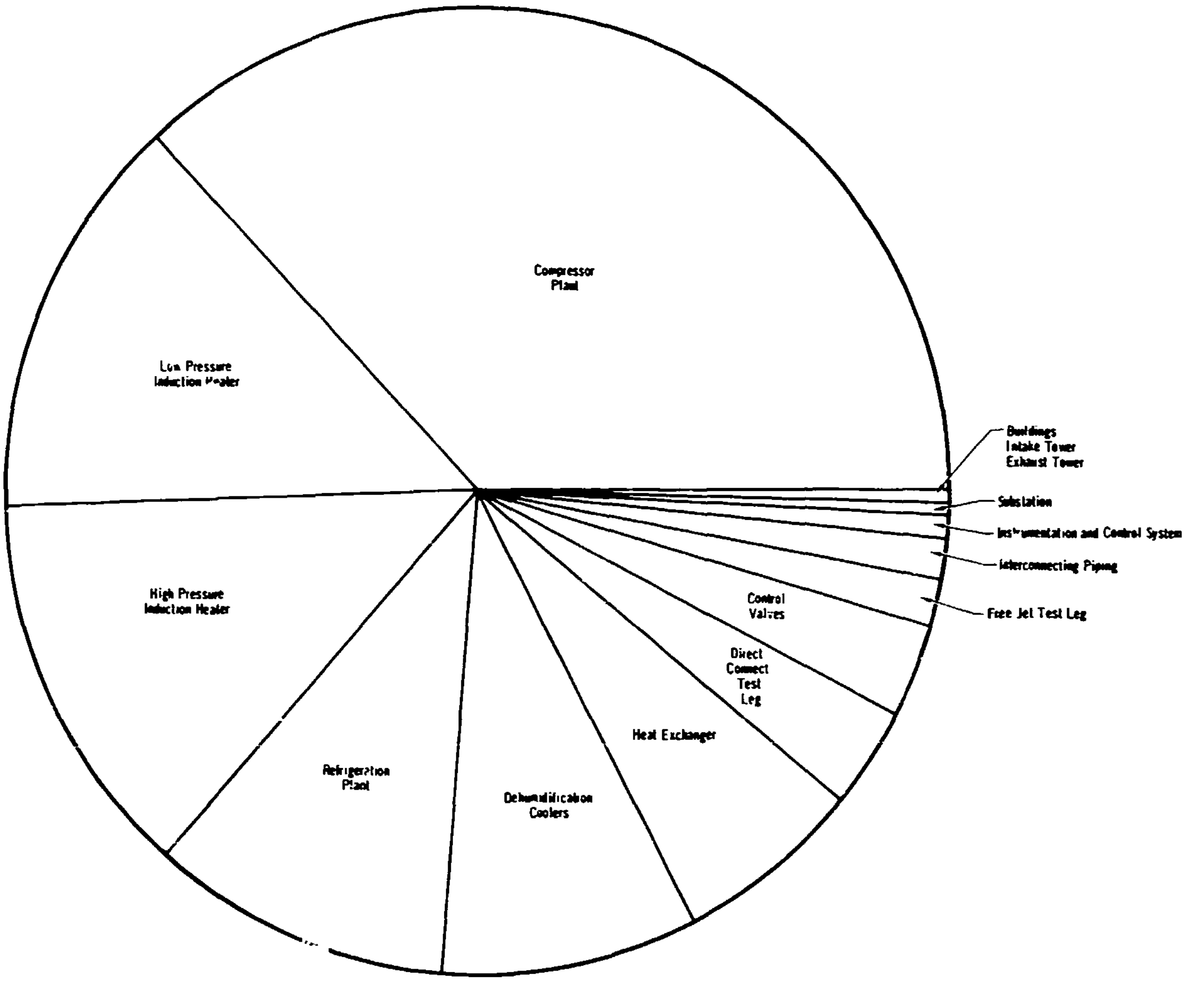
FIGURE 6-13 (Continued)
COST SUMMARY – E20

Facility Component	Cost ($1000's)
Induction Heater (Low Pressure)	
Cold air pipe	①
Heater shell	53
Shaded pole structure	108
Induction coils	20,800
Thermal insulation	2,600
Heater tubes (Refractory Metal)	6,770
Hot air pipe	①
Control valve	②
Gas Turbine-generator packages (6 GE MS-7000 series)	18,000
Development cost	5,700
Subtotal Induction Heater (Low Pressure)	54,031
Oil/Gas Fired Heat Exchanger	20,000
Compressor Plant	
Building	2,600
Compressor	80,000
Piping	7,641
Control valve	11,900
Subtotal Compressor Plant	102,141
Refrigeration Plant	
Building	1,030
Refrigerator	26,800
Piping	172
Control valve	301
Subtotal Refrigeration Plant	28,303
Dehumidification Coolers	23,900
Intake Tower	100
Miscellaneous Valves ②	3,720
Miscellaneous Piping ①	8,320
Substation	2,000
Automatic Control System	
Direct connect leg	400
Freejet leg	400
Subtotal Automatic Control System	800

FIGURE 6-13 (Continued)
COST SUMMARY – E20

Facility Component	Cost ($1000's)
Instrumentation & Data Acquisition System	
Direct connect leg	1,000
Freejet leg	1,000
Subtotal Inst & Data Acquisition	2,000
Test Section Shelter	835
Laboratory and Office Building	450
Total E20 Components	315,093
Contingency @ 10%	31,509
Total E20 Facility Cost	346,602
A & E Fee @ 6%	20,800
Management & Construction Coordination Fee @ 4%	13,860
Grand Total E20	381,262

FIGURE 6-14
DISTRIBUTION OF FACILITY ACQUISITION COSTS - E2C
Total Cost: $381,262,000



6.3 SPECIFIC SITE CONSIDERATIONS

Every one of the general site considerations listed in Section 2.7 must be considered important for E20, except the need for availability of major services or equipment. This facility is of such magnitude that all major systems must be provided specifically for it.

An existing test center must be used for cost effectiveness. The need for a remote area, because of safety hazards and noise, eliminates the major test centers near populated areas. The enormous power requirement which must be provided just for E20 means the facility must be located in an area where extremely large power generation capability exists and is easily expanded, and is available at minimum rates. These requirements point to a major test center located in the TVA network. NASA Huntsville and AEDC fulfill this description.

AEDC is recommended as a site for E20 because of the existing specialization at that center in airbreathing propulsion testing.

6.4 DEVELOPMENT ASSESSMENT

The general rules for the development assessment are presented in Section 2.4. Individual component assessments are contained in each subsection discussion and are summarized here. The following figure lists the individual facility element, cost fraction, and confidence level evaluation.

E20 DEVELOPMENT ASSESSMENT SUMMARY

Item	Cost Fraction (Ki)	Confidence Level (CLi)	Ki CLi	Technical Risk %	Technical Risk Ranking
Direct Connect Test Leg	.032	4.0	.128	2.80	6
Free Jet Test Leg	.015	2.0	.030	2.63	7
Compressor/Exhauster Plant	.372	4.5	1.672	24.44	2
Combustion Heaters	.063	4.5	.283	4.14	5
Induction Heaters	.266	2.0	.531	46.56	1
Cooling Systems	.090	4.0	.360	7.88	4
Refrigeration Plant	.102	4.0	.408	8.94	3
Automatic Control System	.002	5.0	.010	.09	11
Instrumentation	.006	5.0	.030	.26	9
Misc. Valves & Piping	.044	5.0	.220	[illegible].93	8
Substation	.006	5.0	.030	.26	9
Balance of Equip. & Bldgs.	.002	5.0	.010	.09	11
Total	1.000		3.71	100.00	

The numerical confidence level associated with the development assessment of E20 is 3.71. This numerical evaluation is consistent with a subjective evaluation that E20 is a facility with capabilities far exceeding any facility existing or planned, and with resulting severe requirements imposed on the major systems of the facility.

The moderately high development risk associated with this facility implies that, besides being very large in size, certain key elements of the facility, which are critical to its capability, are novel concepts for engine testing and must certainly be proven before commitment to final design. This is the case for the free jet test leg, as described in Section 6.2.?, and also for the induction heater concept. The induction heaters, important because of their very large cost, both absolute and relative, present many specific design problems, not the least of which is their actual capability to produce 2000°F (1093°C) air at the mass flow required, and with reliability. This can only be determined through developmental testing. As noted in Section 6.2.1, it is possible, should the development of a continuous induction heater, or equivalent, fall short of the design goal, to provide the final increment of heating by the use of a carbon based fuel burner. Although not as satisfactory as heated air, the combustion products of such a heater, described in Section 7, can be tailored to have an oxygen concentration very close to that of air. The second highest contributor to the technical risk is the compressor/exhauster plant. Its contribution is high because of its large cost fraction, but there are few problems envisioned in actually providing such a plant.

In summary, E20 is a facility far exceeding any such existing or planned facilities, and although certain components present some design problems, with a careful prototype development program it should be able to meet its performance goals.

6.5 ACQUISITION SCHEDULE AND TIMING

The schedule for acquisition of E20 is presented in Figure 6-15 and is based on the general considerations given in Section 2.8. It is seen that the facility can be available for use in about nine years, which seems reasonable for a facility of such magnitude. Some time elements could be reduced if the program were conducted on a crash basis, but the proposed schedule is conservative and allowance has been made for the usual slippage on a major facility effort. The total period of 10 months from completion of construction to the end of initial calibration embraces facility demonstration tests as well as calibrations and may be longer than would be allowed under the pressure of test program schedule demands. Still, this time should be spent before routine test programs are scheduled. The cost and schedule for acquisition of the complete facility as specified are then:

Cost $381,262,000
Schedule . . . . 104 Months

The acquisition schedule shown in Figure 6-15 is based on providing the full capability as originally defined. The refrigeration plant construction and shakedown is a critical path in this schedule. It is possible to begin operations of the facility without the refrigeration plant being complete. This alternate is shown in the schedule as requiring about 91 months to start operations, with the complete facility capability available at 104 months.

There are a number of alternate possibilities, when considering E20, to reduce initial acquisition costs without degrading its immediate research capability. E20 is sized to accommodate engine sizes and performance projected for the 1980's and 1990's. The initial facility need not then have the performance necessary to test these engines if, as of the time that construction is initiated, these projected requirements have not materialized. Based on mass flows for contemporary study engines, the compressor mass flow could be reduced some 35%, the induction heaters deferred, and the refrigeration plant sized to accommodate only turbojet engines, not the large subsonic turbofans. The free jet test leg construction can also be deferred without harming the basic capability of the facility to do performance and PFRT testing on near-term advanced technology engines. This reduced capability could provide flight duplicated conditions for Mach numbers up to 3.8.

The acquisition schedule for the reduced capability facility would not be changed significantly because other pacing items such as the cooling systems, combustion heaters, etc. are still necessary. The additional compressor capability could probably be provided in a 34 to 38 month period at some later time. The alternative of not immediately providing either the induction heaters or the free jet test leg provides additional time for reduced scale development of these two very high risk components at the same time that the basic facility is being checked out and put into routine operation. Time is also available in the case that planned approaches to these two items do not bear fruit and alternative concepts have to be developed.

Assuming that the preliminary design for the complete facility is accomplished, and the building size capable of accommodating the later additions are supplied, then the costs and schedule of the reduced capability facility are:

COST

E20 reduced mass flow for near-term engines - - -	$209,100,000
Additional cost for acquiring the full capability - - - - - - - - - - - - - - - - - - -	$188,200,000
Total - - - - - - - - -	$397,300,000

SCHEDULE

E20 reduced mass flow for near-term engines - - -	104 Months
Additional time for acquiring the full capability - - - - - - - - - - - - - - - - - - -	38 Months
Total - - - - - - - - -	142 Months

E20 is analogous to the Large Engine Test Facility being planned by AEDC. If LETF was in existence at the time that E20 was considered for acquisition, E20 could probably be considered as add-on growth capability to the basic LETF facility. Probably an additional 150 million dollars would be required to bring LETF to the planned E20 performance level. The E20 facility is of such magnitude that most probably, prior to initiation of an acquisition program, the alternatives would have to be critically reviewed to determine how changes in research capability have affected the original assessment.

6.6 EVALUATION SUMMARY

Development programs for aircraft engines have historically been initiated from an experimental and theoretical technological base sufficient to give reasonable confidence. With the advent of high Mach number engines, the need for this

FIGURE 6–15
ACQUISITION SCHEDULES, TURBOMACHINERY ENGINE RESEARCH FACILITY (E20)

	ACTIVITY
1	Basic Specifications and Construction Concepts
2	Design Criteria
3	Preliminary Design
4	Design of Subscale Hardware for Design Configuration
5	Articulated Test Section
6	Induction Heater
7	Subscale Tests and Results
8	Facility Final Design
9	Direct Connect Leg
10	Free Jet Leg
11	Compressor Exhauster Plant
12	Combustion Heater
13	Induction Heater
14	Dehumidification Coolers
15	Bid Package and Construction Plan
16	Preliminary Site Considerations
17	Site Recommendation
18	Site Preparation Integration Plan Development
19	Letting of Bids
20	Preliminary Site Work and Shop Fabrication
21	Compressor Fabrication
22	Refrigeration Plant
23	Field Fabrication, Installation
24	Direct Connect Leg
25	Free Jet Leg
26	Compressor Exhauster Plant
27	Combustion Heaters
28	Induction Heaters
29	Refrigeration Plant
30	Dehumidification Coolers
31	Demonstration Tests
32	Components
33	Subsystems
34	Complete Facility
35	Shakedown and Calibration
36	
37	Development of Operating Methodology and Assembly of Operating Staff
38	
39	
40	Shakedown and Calibration Minus Refrigeration Capacity
41	
42	
43	
44	
45	
47	
48	
49	
50	
51	
52	
53	
54	
55	
56	
	AFTER GO-AHEAD (MONTHS): 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33
	CALENDAR

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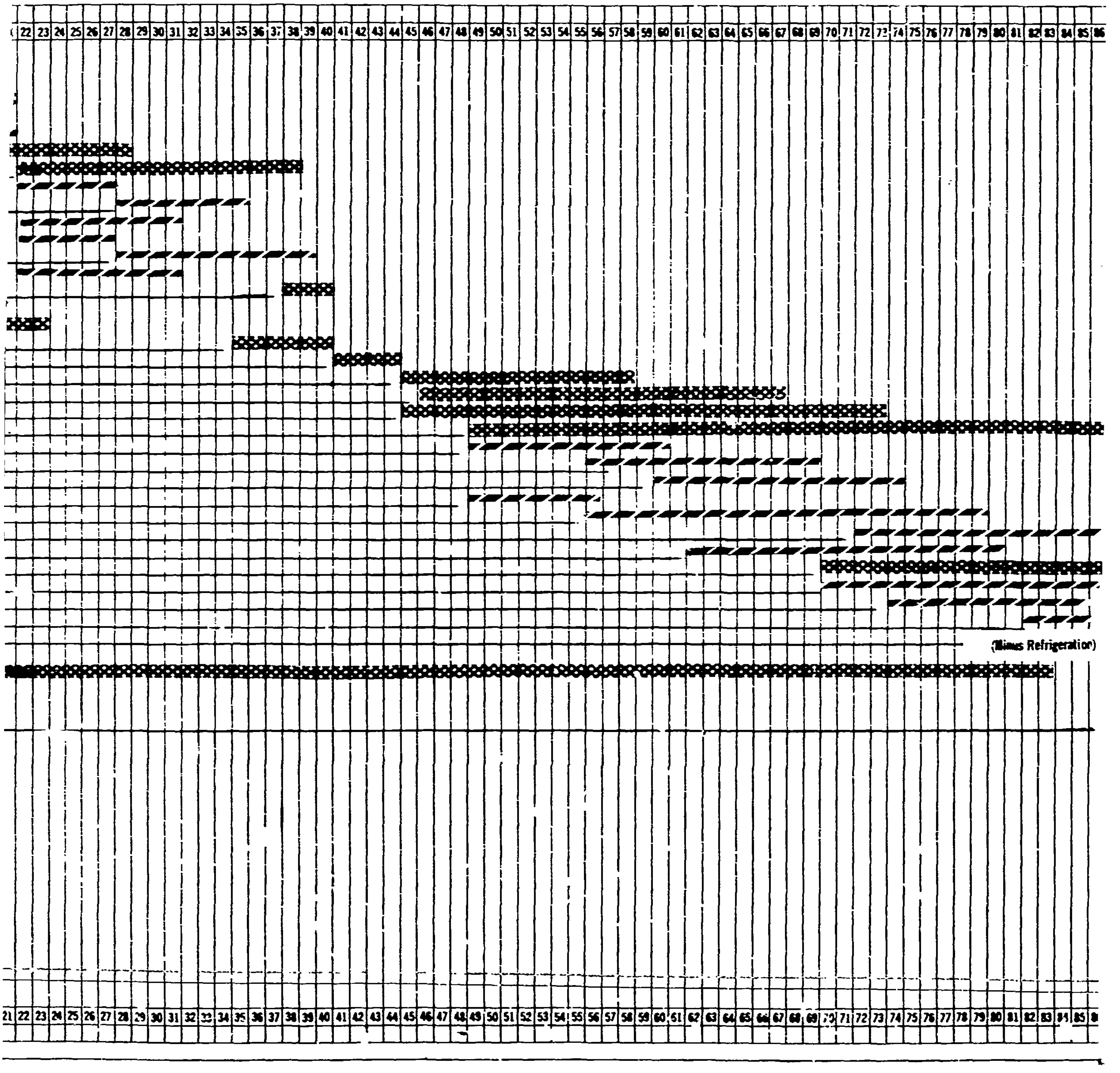

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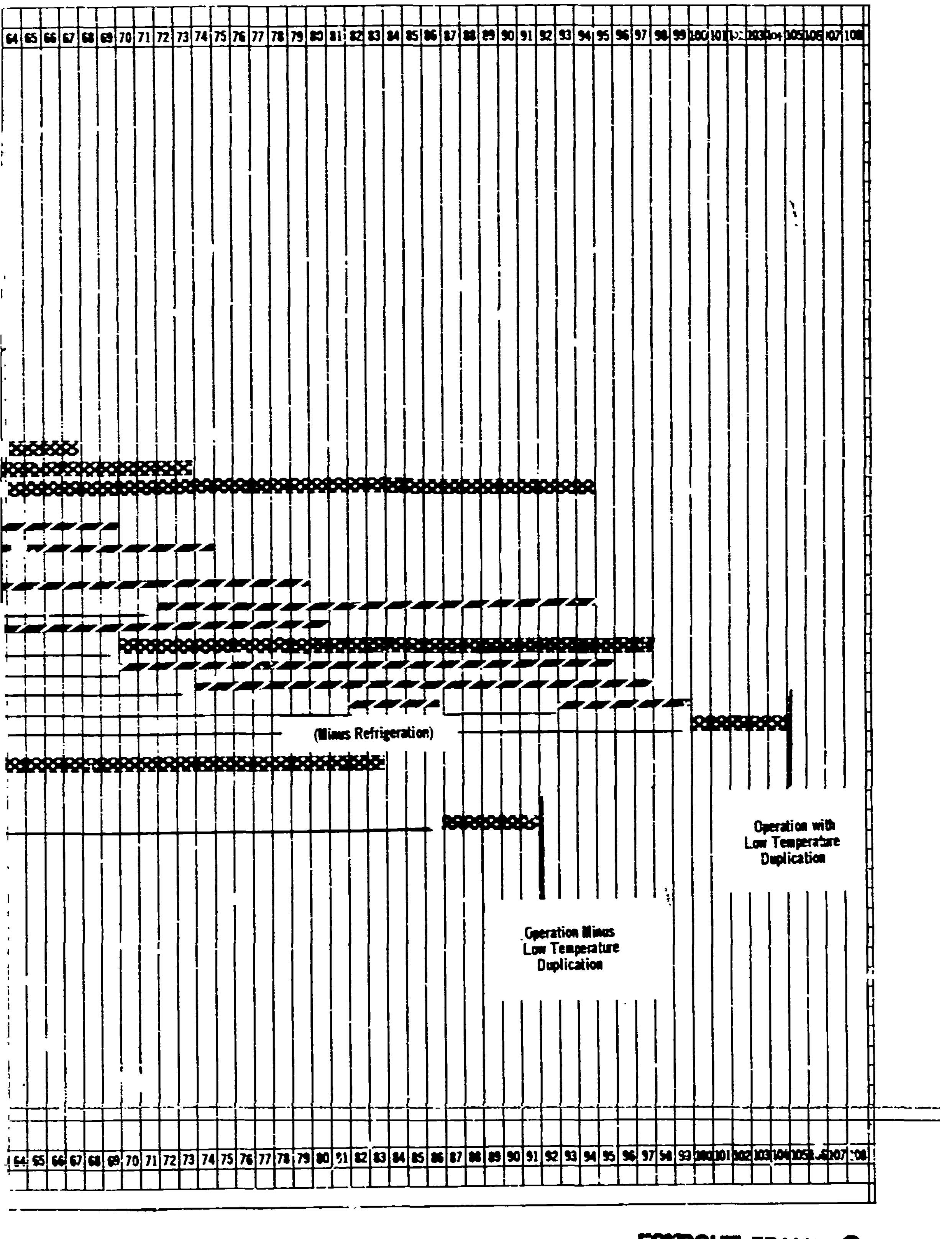

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FOLDOUT F

technological base continues to be important. Engine research facilities described in the HYFAC Study have been proposed in order that the experimental technological base will be available for the airbreathing propulsion systems required for hypersonic aircraft similar to those defined as the HYFAC operational vehicles.

Many problems in the development of turbomachine type engines can be solved on a scale model basis, since engines of this type are essentially aerodynamic machines. Many of these problems, such as compressor and turbine blade design, can be attacked on a component basis, without the need of a complete operating engine or scale model engine. Many facilities exist which are capable of this type of experimental testing.

This engine research facility is designed to accommodate full scale operating engines throughout the complete altitude-Mach number envelope flown by the HYFAC operational vehicles, up to Mach 5.5. This envelope was discussed in detail in Section 6.2 and was shown in Figure 6-2.

Continuous operation of engines for long term PFRT and performance testing is the primary type of testing done in a facility of this type. Many classes of problems can be solved during such testing.

o Investigation of altitude operating characteristics as influenced by such factors as compressor stall, combustion blowout, and high altitude engine re-start.

o Investigation of inlet flow distortion through the use of distortion screens in the direct connect duct or through the use of a modified direct connect apparatus which more nearly duplicates the aircraft inlet duct and can provide time-variant flow distortions (described in more detail in Section 6.2.1).

o Simulation of inlet pressure and temperature transient effects on engine operation, such as those produced by ingestion of high pressure and temperature gases resulting from machine gun operation.

o Evaluation of engine dynamics and controls. Control problems investigated are those related to engine starting and acceleration, the avoidance of operating limits such as combustor blowout and compressor stall, protection of the engine against damage by over-temperature and excessive stress, maintenance of optimum conditions of operation, and achieving stable operation and rapid response to changing load demands.

Full scale testing of engines with flight duplicated conditions is essential for PFRT and perform[illegible]uation and very important for tests involving phenomena which are non-scal[illegible] [illegible]bustion processes and dynamic coupling effects between inlet du[illegible] [illegible] combustor.

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The size and cost of the facility is determined directly as a function of the size of the engines to be accommodated. The composite inlet flow requirements of the test engines determine the total facility mass flow schedule. Definitions of the engines considered, and their inlet flow requirements, are presented in detail in Section 6.2. These requirements define the capability of E20 in terms of basic flow parameters. Existing facilities provide continuous flow on a smaller scale than E20, and are satisfactory for current test requirements. The three-dimensional plot of weight flow, pressure, and temperature shown (Figure 6-16) permits a comparison between existing and planned continuous engine test facilities and E20. It is obvious from this sketch why E20 is so expensive in comparison to existing facilities, since extension of facility capability, particularly weight flow and temperature, is very costly.

During Phase III, a final list of 278 Research Tasks, each task being a subset of the 78 Research Objectives, was defined. This list of research tasks was used to determine the research potential of each candidate research facility considered during Phase III. Details of this analysis and evaluation are contained in Volume IV, Part 3, and are summarized below.

E20 was identified to have contributions to many Research Objectives. Specific engine research for the L2, C1, and M1 vehicles applied to E20. Some capability was noted even for M2, however, since the free jet test leg provides full flight conditions, including Mach number, up to Mach 5, and can be used for aerothermodynamic testing of structures, boundary layer research, and so forth.

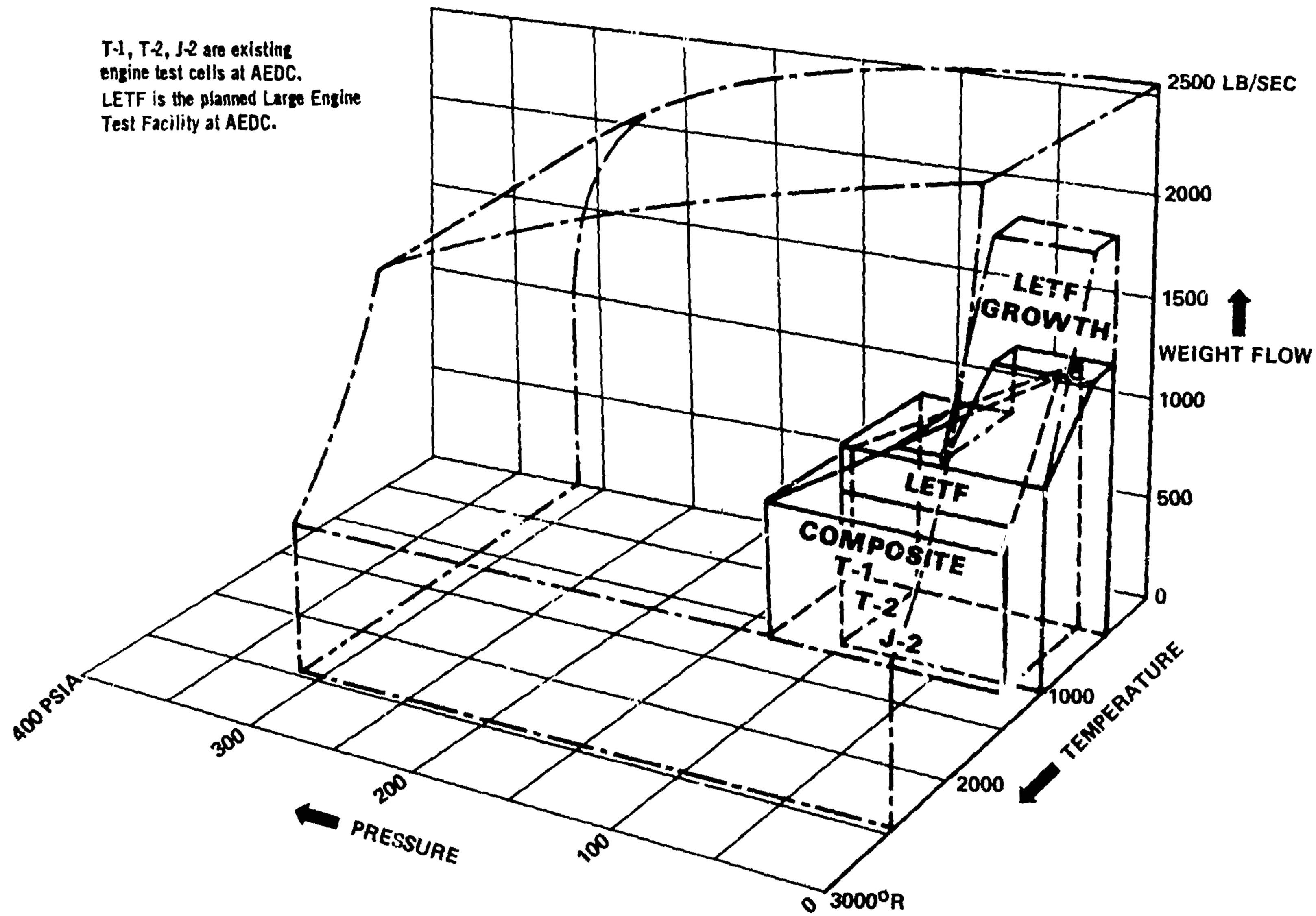
In terms of research capability, E20 was evaluated as providing about a 40% increase over existing similar facilities. Considering the already demonstrated capability of existing facilities, this judgement reflects the need for large sized, high pressure and temperature facilities operating on a continuous basis and the influence that problems in this flight regime can have on the design performance of hypersonic aircraft. This facility therefore is very relevant to the research and development capability required for potential operational aircraft.

Figure 6-17 summarizes the performance, costs, development assessment and design characteristics of E20. The sketch shows the total facility flow available along with the specific requirements of the engines and the free jet test leg.

The moderately low confidence level associated with this facility implies that, besides being very large in size, certain key elements of the facility, which are critical to its capability, are novel concepts for engine test facilities and must be proven before commitment to final design.

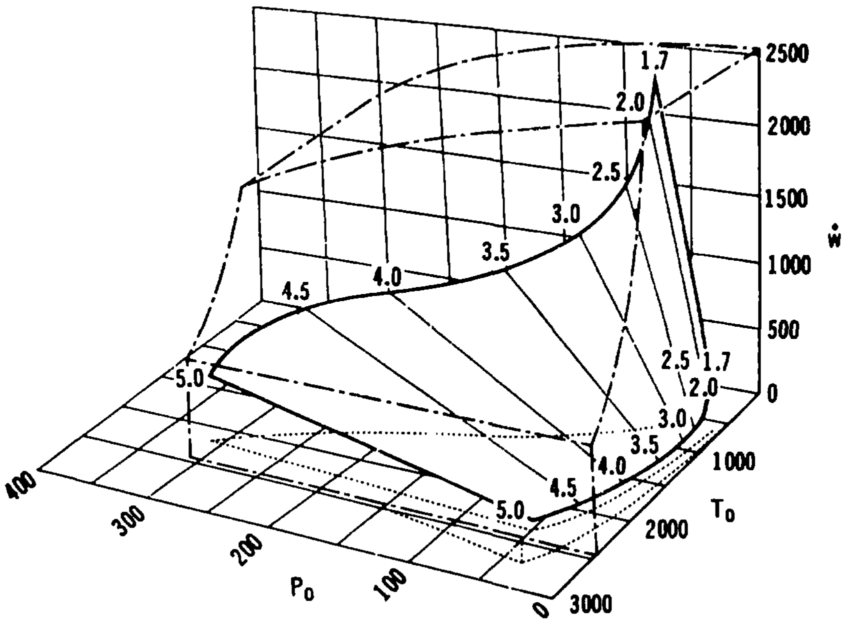
The size and capabilities of E20 make it a major national engine test facility. Although smaller versions of this type of test capability, like the proposed LETF at AEDC, are adequate for near-term advanced technology engines, the very long lead time required for E20 means that serious consideration should be given now to its design and construction if the capability to test the defined engines is desired by 1980.

FIGURE 6-16
COMPARISON OF E20 INLET FLOW CAPABILITIES
WITH THOSE OF EXISTING AND PROPOSED FACILITIES



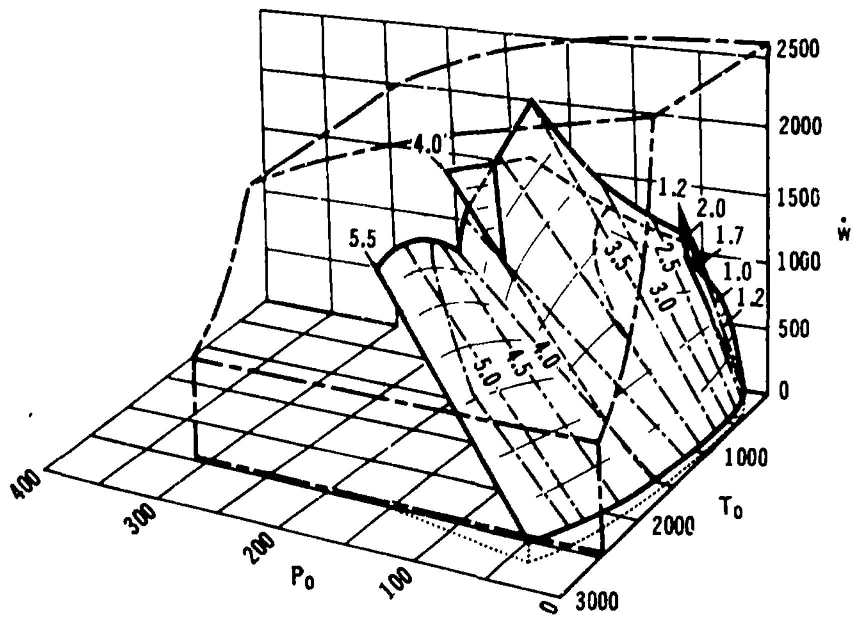
T-1, T-2, J-2 are existing engine test cells at AEDC.
LETF is the planned Large Engine Test Facility at AEDC.

FIGURE 6–17
PERFORMANCE AND SPECIFICATIONS FOR E20



Freejet Testing

Freejet Test Section:
8 Ft x 4.5 Ft (2.4 m x 1.4 m)
Mach Range: 0 to 5.0



Direct Connect Testing

Direct Connect Maximum Engine Size:
12.0 In. (3.05 m)
Mach Range: 0 to 5.5

Cost – $381,262,000
Confidence Level = 3.71 on a scale from 1 to 5, where 5 represents low risk existing equipment technology and 1 represents high risk theoretically predicted technology.

7. DUAL MODE RAMJET ENGINE RESEARCH FACILITY (E9)

The development of an airbreathing hypersonic aircraft depends on a vigorous and continued research effort in hypersonic ramjet or scramjet propulsion systems. Many questions of feasibility have been answered favorably by the investigation of several small research engines. There are many key areas however, requiring additional research when considering the technology base necessary to develop a major operational hypersonic aircraft system. The concept represented by E9 is an attempt to adapt existing technology from both aerospace and non-aerospace industries to provide the needed research capability and facility size at costs lower than previously estimated.

This facility consists of a single test leg with several modes of operation and testing capability depending upon the combination of equipment being utilized. The prime mission of the facility is to test scramjet engines through a flight Mach number range of 3 to 10 with the local engine flow parameters flight duplicated. The secondary mission is to utilize the temperature and pressure capability of the heater systems to perform thermo/structural testing. This option is available by removing the engine test module system and piping and substituting one of three nozzles, test cabin, and diffuser arrangements capable of Mach 6, 9 and 12 operation.

E9 can accommodate engine modules up to 16.3 inches (.41 m) high and 45.5 inches (1.15 m) wide, which represent a full scale scramjet engine module for a 600,000 lb (270,000 kg) class aircraft. The thermo/structural legs, which are interchangeable with the scramjet test section, provide the following size capability.

Mach Number	Nozzle Exit Diameter ft (m)	Constant Velocity Core Diameter ft (m)
6	6.45 (1.97)	5.7 (1.74)
9	12.2 (3.72)	8.8 (2.69)
* 12	18.6 (5.67)	9.0 (2.75)

* flight velocity not duplicated, but Mach number and density altitude are duplicated.

This facility is unique in capability with a dual mode of operation, i.e., continuous and intermittent. This concept, combined with the test conditions available, allows scramjet testing on a real time trajectory. This has the advantage of heating the structural materials of the test article in a manner identical to the flight case. The continuous operating conditions are achieved utilizing an oil-fired heat exchanger and carbon fueled combustor in combination. With the engine operating at flight conditions, in vitiated air, the intermittent air heater cycle is established with no change in test conditions except for the gas stream composition. After the intermittent cycle is completed, the facility can revert to continuous operation or be shut down.

The following table lists some of the test capabilities of the dual operational modes.

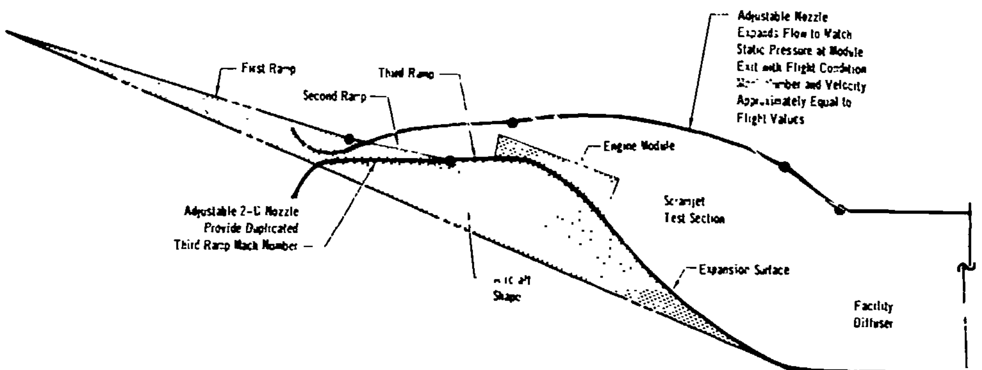
Mach No.	P_o psia	P_o (N/cm^2)	T_o °R	T_o (°K)	Continuous Operation: Oil-Fired Heat Exchanger	Continuous Operation: Carbon Based Fuel Combustor	Intermittent Operation: Oil-Fired Heat Exchanger	Intermittent Operation: Refractory Storage Heater
3	50	34.5	1080	600	X		X	
4	140	96.5	1600	890	X		X	
5	250	172	2200	1222	X		X	
6	360	248	3000	1665	X	X		X
7	760	523	3800	2110	X	X		X
8	1500	1033	4650	2590	X	X		X
8.6	3000	2070	5200	2890	X	X	--	--
9	3000	2070	5700	3170	X	X	--	--
9.2	3000	2070	6000	3330	X	X	--	--
10	3000	2070	7000	3890	X	X	--	--

In Phase II, size tradeoffs were made to determine the effect on facility component specification, costs, and technical risk. It was found that the baseline facility size could be increased to accommodate scramjet engine modules up to 27.6 ft^2 capture area (2.56 m^2) without incurring unacceptable development risks. As the input data was refined, some of the facility components were found able to accommodate increased mass flows without substantial changes in size. Therefore, the facility defined in Phase III has a 150 percent increase in engine module size from the Phase II definition.

The performance of E9 was based on the assumption that flight duplicated conditions should be provided for scramjet engine research and development. Because of the extremely difficult technical and mechanical problems associated with free jet testing a large integrated scramjet engine, the approach taken was to provide the local flight duplicated conditions (Mach number, velocity and density) for the ramp just upstream of the engine cowl. Also by restricting the test article to an individual module instead of the entire engine, a facility size consistent with current technology would result. Thus the local internal and external flow could be simulated from the last ramp, through the combustor to the airframe-expansion nozzle, as depicted in Figure 7-1 (Reference 3).

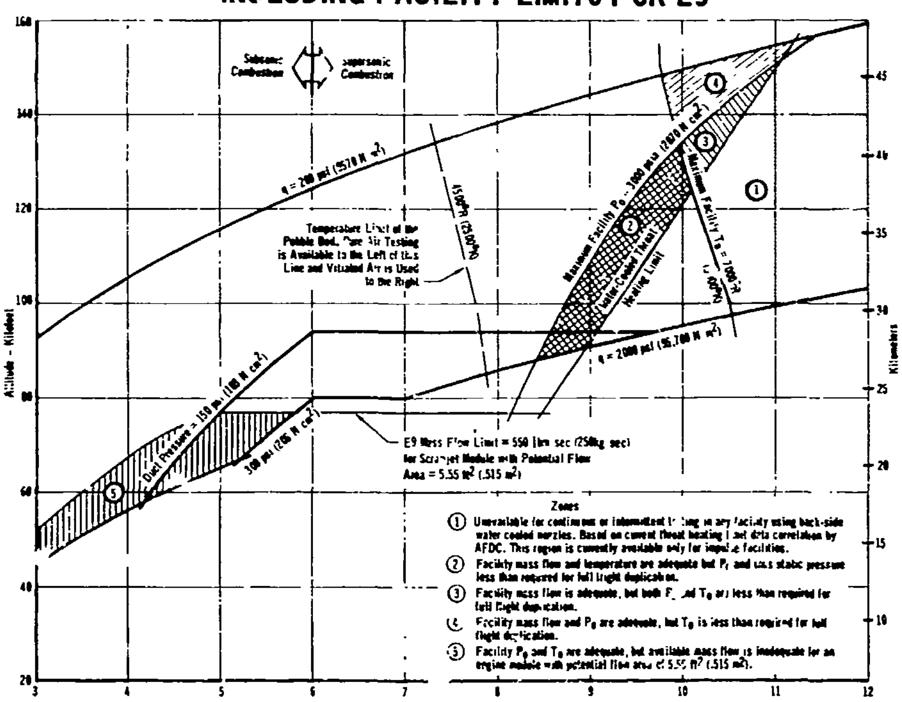
This concept reduces the facility size and power required to provide scramjet engine test capability by approximately a factor of eight. This scramjet test section can incorporate all of the features of an aircraft operational engine. The module and third ramp can be cryogenically cooled panels duplicating actual structural features of the aircraft. The lower nozzle surface can be constructed of materials identical to those of the aircraft and operated at the same surface temperatures. This provides realistic boundary layer temperature profiles, unattainable in heavily water cooled conventional cold wall nozzles. With this facility the actual engine operation can be duplicated over the range of flight conditions.

FIGURE 7-1
CONCEPT OF MODIFIED DIRECT CONNECT SCRAMJET TEST SECTION



The operational performance of E9, in terms of flight duplicated conditions is shown in Figure 7-2.

FIGURE 7-2
FLIGHT BOUNDARIES ASSUMED FOR HYFAC CSJ AND SJ ENGINES, INCLUDING FACILITY LIMITS FOR E9



The upper and lower lines represent the HYFAC potential operational aircraft flight corridor. The jog in the low altitude boundary represents a 300 psia (206 N/cm^2) subsonic duct internal pressure limit to Mach number 6 where probable transition to supersonic combustion occurs. The throat cooling limits represent the maximum conditions for which back-side film water cooled nozzles have survived. The two temperature limits show the maximum temperatures which can be achieved using air, operating intermittently (4500°R, 2500°K) and using carbon combustion products, air, oxygen mixture, operating continuously (7000°F, 3900°K).

A primary consideration in the choice of providing continuous operation was the requirement that eventually any engine system must be qualified for flight. E9 was so designed to provide a preliminary flight rating test (PFRT) in the time span of a few months. Another factor which significantly influenced the design of E9 was the need to test cryogenically cooled scramjet engine modules. It was judged highly unlikely that a chilled-down liquid hydrogen engine could withstand the sudden start of a zirconia storage heater facility operating at maximum temperature.

The actual concept for utilizing the carbon combustion arose from this consideration. The oil-fired heat exchanger and carbon combustor would be utilized to thermally precondition the scramjet engine module analogous to what occurs during takeoff-climb and acceleration of an operational aircraft. However, as the performance and characteristics of the carbon system were developed by the Cabot Corporation it became apparent that this operating mode could just as well provide an excellent, continuous flow scramjet facility. The carbon combustion products, mixed with air and oxygen, results in a good simulation of the properties of air. The deleterious effects of water vapor are not present in the form of reduced molecular weights, alteration of the hydrogen combustion chemistry, and more rapid degradation of coated refractory metal surfaces.

The following sections describe the work done to refine the definition of the scramjet engine sizes, and the facility design and performance as well as the result of this refinement process in terms of facility descriptions and costs, safety considerations, specific site criteria, development assessments, and facility acquisition schedule.

7.1 REFINEMENTS IN DESIGN AND PERFORMANCE

The work done in Phase III on this facility was concentrated on improvement of the design and specifications of the test legs and facility systems. The major goal was to refine the specification so that the facility will meet its performance definition at a reasonable acquisition and operating cost. With additional data fro AEDC and the Cabot Corporation, the performance of E9 was substantially improved. The following tasks were performed in order to attain the goal of improved facility description and performance, and minimized costs.

(1) Structural and Mechanical layout of both test legs was done by Fluidyne Engineering Corporation, using as a starting point the Phase II facility sketches. Their experience in designing and operating zirconia heaters, and their research efforts sponsored by the Air Force in support of the TRIPLTEE project greatly added credibility to the design of the zirconia heater system for E9. Their experience in facility design was useful in searching out and solving problem areas and in obtaining a detailed facility description. Test leg cost estimates were done by MCAIR using the Fluidyne drawings as a basis.

(2) A much more detailed analysis of the total compressor-exhauster requirements was performed. A by-product of this work was analysis of the flow cooling required to reduce the exhauster inlet flow temperatures to an acceptable level and reduce exhauster inlet volume flow. Specifications and costs of a plant fulfilling the developed requirements were worked out by Allis Chalmers.

(3) Scramjet engine sizes were re-examined based on sizing criteria more realistic for engines integrated into the basic airframe. Details are presented in the latter portion of this section.

(4) The maximum facility mass flow limits were redefined based on the AEDC and Fluidyne data, reflecting this in increased engine size testing capability.

(5) The carbon based fuel combustor concept initially proposed by the Cabot Corporation was refined. With a significant contribution of their own effort, Cabot was able to propose a system which could provide the required hot gas mass flows at reduced costs, high temperatures, and with better air simulation. The details of this process are proprietary to the Cabot Corporation and are not presented in this document. The conditions which the carbon fuel combustor can produce are not considered proprietary and are given.

(6) Conversations with the staff of AEDC were held to determine the potential of E9 to be integrated into the AEDC complex. The similarity of E9 to TRIPLTEE is such that it appears the carbon combustor and the scramjet test section can be considered as growth versions of the basic TRIPLTEE concept. Integration of the E9 concept into TRIPLTEE would result in that basically intermittent facility acquiring a continuous run capability.

(7) Analysis of the air pre-heater requirements in this phase developed that this particular area was considerably under-estimated in the earlier work. Both costs and technical feasibility were poorly defined. The alternate use of an oil-fired combustion heat exchanger was investigated to reduce the high costs of electric heaters.

(8) Analysis of safety hazards to personnel, test article and facility were performed by Fluidyne. Procedures, safety interlocks, special subsystems, and control system rationale needed to operate the facility safely were described.

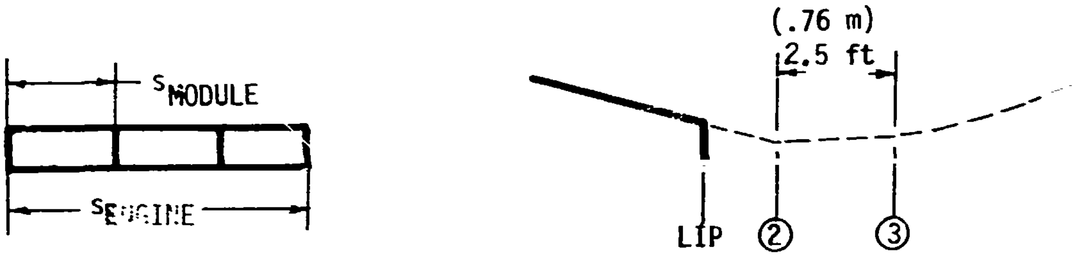
(9) As the elementary cost analysis in Phase II showed, the costs of support systems were the dominating factor. In addition to obtaining much more sophisticated equipment requirements, costs of all equipment were estimated, where possible, by equipment manufacturers. These estimates are based on gross specifications and not a detailed engineering study of each individual component. The cost estimated by the vendors and manufacturers, therefore, are engineering judgements based on their industrial experience.

(10) Analysis of the problems and risks associated with each major component and system of the facility was performed. A composite assessment for the entire facility was calculated. This assessment attempts to quantify the facility confidence level and identify major problem areas.

(11) The analysis of the construction problems and the development and acquisition schedule for the test legs was made by the Fluidyne Engineering Corporation. The schedule covers everything from the development of the basic specifications to facility shakedown and calibration. Similar analyses by MCAIR have been made and included in the acquisition schedule for the compressors, exhausters, coolers, and heater systems.

(12) An evaluation of the facility was made summing up its ability to perform the research tasks in relation to its acquisition and operating cost.

The definition of the scramjet engine size was improved as stated in Item 3, the following is the development of the improved definition. The facility specified in Phase II was based on preliminary scramjet engine configuration. This configuration definition has been further refined so that the ratio of module height to width has changed, altering the relative proportions of the scramjet engine test section nozzle. The Phase II definition was:



$s_{MODULE} \leq \begin{matrix} 4.2 \text{ feet} \\ (1.28 \text{ m}) \end{matrix}$

$Ac \approx .045\ Sw$

$W_{TO} \approx 98\ Sw$ (English)

$489\ Sw$ (SI Units)

$8 \leq \dfrac{s_{ENGINE}}{h_{LIP}} \leq 10$

$h_{LIP} = 2\ h_2$

$h_3 = 1.2\ h_2$

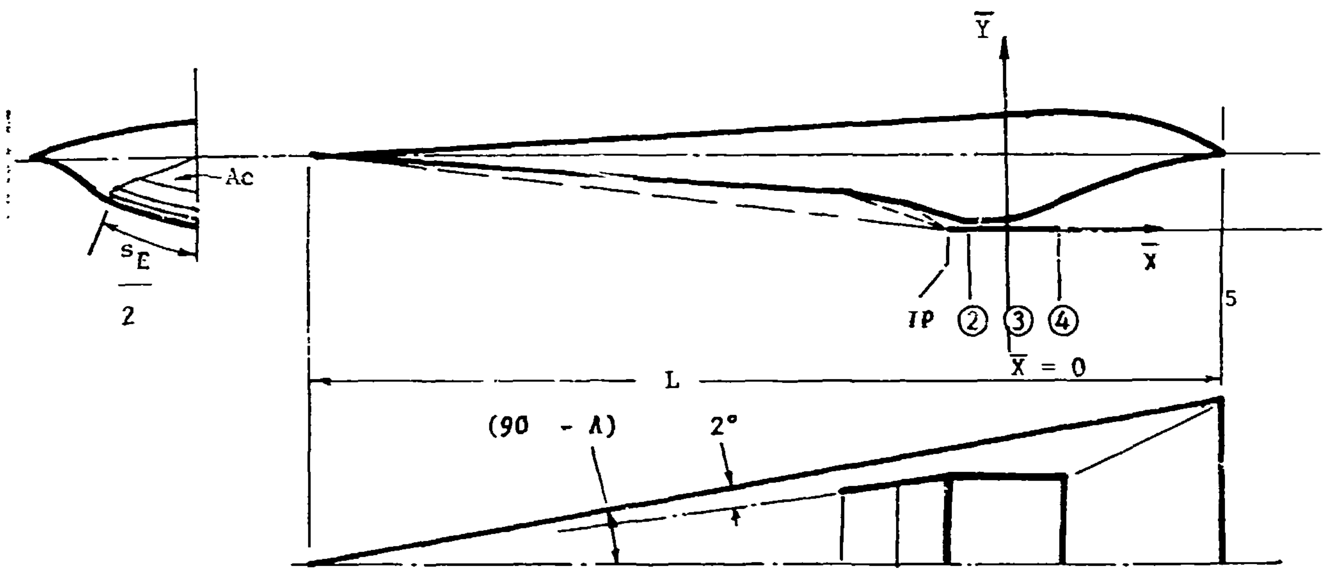
$s_{ENGINE} = Ns_{MODULE}$

where Ac = engine geometric capture area
Sw = vehicle wing area (ft^2/m^2)
W_{TO} = takeoff weight (lb/kg)
N = number of modules.
h = duct height

The criteria for the unsupported wall length for the cryogenically cooled wall panel was estimated from previous MCAIR studies. Based on these ground rules, the engine sizes are discussed in detail in Volume III, Part 1, Section 6.3.

For Phase III the scramjet engine definition was refined to be more compatible with an aircraft concept as depicted in Figure 7-3. This figure defines the geometric parameters assumed. For the calculations of engine size, areas, and wetted areas which follow, the following assumptions were made:

FIGURE 7–3
SCRAMJET GEOMETRIC DESCRIPTION



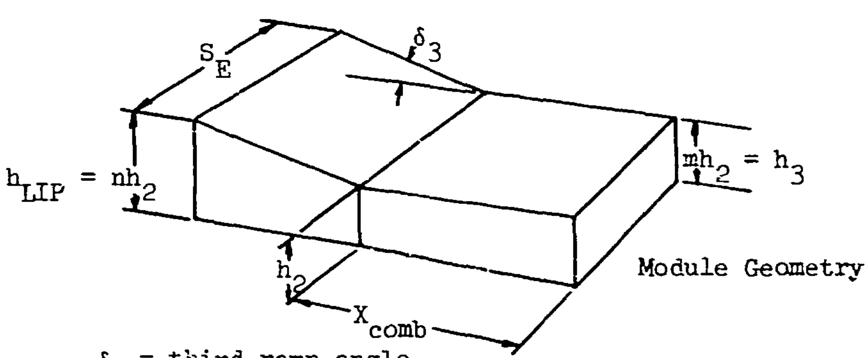
L = Aircraft Length   Λ = Wing Sweep Angle

S_E = Scramjet Module Width A_c = Geometric Capture Area

$\overline{X} = \frac{X}{h_3}$ $\overline{Y} = \frac{Y}{h_3}$

h_3 = height of module at station (3) = mh_2

h_{LIP} = height of module at module lip = nh_2



δ_3 = third ramp angle

X_{comb} = combustor length

Ramp angles, measured from aircraft waterline

$\delta_1 = 4°$ $\delta_2 = 8°$ $\delta_3 = 13°$

Shock wave angles, calculated at Mach 12:

$$\psi_1 = 6^\circ \qquad \psi_2 = 15.2^\circ \qquad \psi_3 = 20.9^\circ$$

Geometric proportions:

$$n = \frac{h_{LIP}}{h_2} = 2 \qquad m = \frac{h_3}{h_2} = 1.$$

Wing Sweep Angle, Λ, = 80°

X_{comb} = minimum distance necessary for complete combustion, taken to be 30 in (.91m) for all engine sizes.

The length of the aircraft can be expressed in terms of the scramjet module dimensions, and as a function of wing area and sweep angle.

$$L = mh_2\overline{Y}_5 \cot \psi_1 + (n-1)h_2 \cot \delta_3 + X_{comb} + mh_2\overline{X}_5$$

$$L = \sqrt{Sw \tan \Lambda}$$

The width of the scramjet engine can be expressed as:

$$S_E = 2K_1 m h_2 \cot \psi_1 \cot (\Lambda + 2^\circ)\ \overline{Y}_5 = K_1 C_1 h_2 \overline{Y}_5$$

where $C_1 = 2m\,[\cot \psi_1 \cot (\Lambda + 2^\circ)]$

and K_1 = factor allowing for the curvature of the bottom of the aircraft. K_1 is about 1.05-1.07 for HYFAC-type configurations.

The inlet area to the combustor is:

$$A_2 = S_E h_2 = K_1 C_1 h_2^2 \overline{Y}_5$$

The cowl area, at the scramjet module entrance is:

$$A_{cowl} = S_E h_{LIP} = S_E n h_2 = K_1 C_1 n h_2^{\,2}\ \overline{Y}_5$$

The geometric capture area, A_c, can be calculated as:

$$A_c = \frac{K_2 S_E h_2 \overline{Y}_5\ m}{2} = \frac{K_2 C_1 h_2^{\,2} \overline{Y}_5^{\,2} m}{2}$$

where: K_2 = area correction factor which allows for the curvature of the bottom of the aircraft. K_2 is about 1.11 to 1.13 for HYFAC-type configurations.

The ratio of geometric capture area to the wing area of the aircraft is then:

$$\frac{A_c}{S_W} = \frac{K_2 C_1 h_2{}^2 \bar{Y}_5 m}{2\ L^2 \cot\Lambda}$$

This ratio was taken to be 0.045 for all cases in this computation, and represents a practical upper limit of module size which can be physically accommodated on highly swept aircraft. Documentation is contained in MCAIR Report F666, Volume 6, Hypersonic Scramjet Vehicle Study (1967). For this case, $\bar{Y}_5$ and $\bar{X}_5$ were solved, with n = 2 and m = 1.2, and found to be:

$\bar{X}_5 = 62.0 \qquad \bar{Y}_5 = 16.8$

The following table illustrates the contours of the exhaust nozzle.

$\bar{X}$	$\bar{Y}$
0	1.0
1.29	1.50
3.58	2.60
7.94	4.32
12.66	6.09
18.12	7.98
24.36	9.76
32.60	11.80

$\bar{X}$	$\bar{Y}$	(Ac/Sw)	
41.4	13.6	.062	
49.9	15.0	.054	
56.4	16.0	.049	
62.0	16.8	.045	← Selected Value
65.0	17.8	.041	
70.0	19.0	.035	

The exit nozzle contour is not tabulated to full theoretical expansion where the nozzle static and free stream pressure are identical, which would occur at $\bar{X}$ = 150 or greater.

The total wetted area of the engine, per individual module, can be expressed as:

$$\left.\frac{S_{wet}}{A_{cowl}}\right]_{\substack{per\\module}} = \frac{2}{n}\left(\frac{X_{comb}}{h_2}\right) - \left(\frac{n-1}{n}\right)(\cot\delta_3 + \csc\delta_3) + \left(\frac{m+1}{n}\right)\left(\frac{X_{comb}}{h_2\bar{Y}_5}\right)\left(\frac{N}{C_1}\right) + \left(\frac{n^2-1}{n}\right)\left(\frac{\cot\delta_3}{\bar{Y}_5}\right)\left(\frac{N}{C_1}\right)$$

where N = number of individual modules comprising the engine.

Figure 7-4 shows the engine module sizes and the ratio of wetted area to cowl area, based on these equations, for series of aircraft sizes. They range from a very large horizontal take-off aircraft to a small research model. Data is also shown on the Phase II engines for comparison. The use of $\bar{X}_5$ = 62 provides the same ratio of capture area to wing area used in the Phase II analysis. S_W was taken to be .0102 WTO (English units) or .00205 WTO (S.I. units), as in Phase II.

The combustor height, h_2, was calculated for these cases by:

$$h_2 = \sqrt{\frac{A_c}{r_c C_1 Y_5}}$$

where r_c = contraction ratio = $\frac{A_c}{A_2}$ and was taken to be 11.3. This value was established in the previously mentioned HSVS study as being near optimum. The number of modules used in each engine was calculated by the rule:

$$N \geq \frac{S_E}{42 \text{ in}} \text{ or } \left(\frac{S_E}{1.07\text{m}}\right)$$

where 42 in (1.07m) represents an approximate maximum width of an individual, unsupported cryopanel, and is based on an unpublished study by MCAIR structures group. It represents the trade-off point where increasing the module width incurs excessive weight penalties.

As presented in Figure 7-4, the refinement of the engine geometry definition altered the height-to-width ratio of the inlet module. The ratio of wetted area to capture area was used as an index of the change in thrust which might be expected as a result of internal frictional forces. In other words, if the frictional forces represented a small percentage of the gross thrust, the changes in these frictional forces could be theoretically accounted for in model tests so long as the frictional forces did not become a dominating factor as module size decreased. Assuming a 7% frictional loss for the largest engine, then the estimated increase in frictional thrust losses were scaled as shown in the following table, including increases in skin friction coefficient as well as wetted area changes.

$\frac{A_c}{N}$ ft^2 (m^2)	900 (83.5)	480 (44.5)	270 (25.1)	140 (13.0)	80 (7.42)	30 (2.79)	10 (.929)	4 (.037)	1 (.093)
Scaled Frictional Thrust Losses (percent)	7	8	9	11	13	16	32	50	100

Thus engine sizes down to 30 ft^2 (2.8 m^2) probably represent the smallest scaled engine sizes which meaningful scale performance could be extracted, for the conditions analyzed.

From Figure 7-4 it is evident that the cooling requirements increase rapidly as module size is reduced due to increasing surface areas per unit capture area. Therefore, experimental results on cooling requirements from subscale engine tests are necessarily pessimistic. Assuming scramjet engines applicable to the potential operational hypersonic aircraft to be in the 180 to 480 ft^2 (44.5 to 16.7 m^2) capture area category and a Mach number 12 research airplane to be about 43 ft^2 (4 m^2) capture area, the 30 ft^2 (2.8m^2) size represents a minimum size research module for the operational hypersonic aircraft, and nearly a full scale module for the research aircraft.

FIGURE 7-4
SCRAMJET SIZES, COMPARISON PHASE II DEFINITION WITH PHASE III DEFINITION
(ENGLISH UNITS)

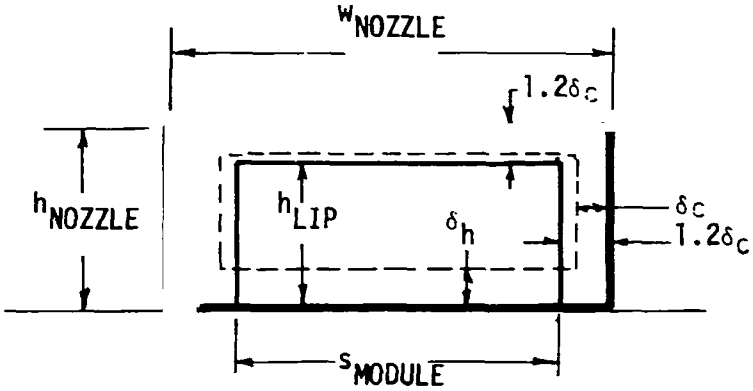
			PHASE II $C_1=18$						PHASE III $C_1=54$					
A_c (ft^2)	S_w (ft^2)	W_{TO} (lb)	N	h_2 (ft)	s_E (ft)	$\frac{S_E}{N}$ (ft)	$\frac{A_c}{N}$ (ft)	$\frac{S_{wet}}{A_{cowl}}$ (module)	N	h_2 (ft)	s_E (ft)	$\frac{S_E}{N}$ (ft)	$\frac{A_c}{N}$ (ft^2)	$\frac{S_{wet}}{A_{cowl}}$ (module)
900	20,000	1,960,000	10	2.16	38.8	3.88	90.0	7.0	16	1.20	66.3	4.14	56.2	7.1
480	10,700	1,050,000	7	1.54	27.7	3.96	68.6	7.1	12	.880	48.3	4.02	40.0	7.7
270	6,000	589,000	5	1.15	20.7	4.14	54.0	7.4	9	.660	36.3	4.03	30.0	8.4
140	2,890	283,000	4	.829	14.9	3.72	35.0	7.9	7	.474	26.1	3.73	20.0	9.9
80	1,789	174,000	3	.627	11.3	3.76	26.7	8.7	5	.360	19.7	3.94	16.0	11.5
30	665	65,100	2	.373	6.7	3.36	15.0	11.4	3	.210	12.7	4.23	10.0	16.3
10	222	21,800	1	.233	4.2	4.19	10.0	15.1	2	.133	7.3	3.65	5.0	23.6
4	89.0	8,740	1	.141	2.5	2.54	4.0	23.8	1	.080	4.4	4.41	4.0	35.0
1	22.2	2,180	1	.076	1.3	1.32	1.0	40.0	1	.042	2.3	2.31	1.0	64.0

See Figure 7-3 for definition of nomenclature pertaining to scramjet engine.

FIGURE 7–4 (Continued)
SCRAMJET SIZES, COMPARISON PHASE II DEFINITION WITHPHASE III DEFINITION
(S.I. UNITS)

			PHASE II $C_1 = 18$						PHASE III $C_1 = 54$					
A_c (m^2)	Sw (m^2)	W_{TO} (kg)	N	h_2 (m)	s_E (m)	$\frac{S_E}{N}$ (m)	$\frac{A_c}{N}$ (m)	$\frac{S_{wet}}{A_{cowl}}$ (module)	N	h_2 (m)	s_E (m)	$\frac{S_E}{N}$ (m)	$\frac{A_c}{N}$ (m)	$\frac{S_{wet}}{A_{cowl}}$ (module)
83.6	1858	889,041	10	.658	11.8	1.18	27.4	7.0	16	.366	20.2	1.26	17.1	7.1
44.6	994	476,272	7	.469	3.4	1.21	20.9	7.1	12	.268	14.7	1.23	12.2	7.7
25.1	557	267,166	5	.351	6.3	1.26	16.5	7.4	9	.201	11.1	1.23	9.1	8.4
13.0	268	128,367	4	.253	4.5	1.13	10.7	7.9	7	.144	8.0	1.14	6.1	9.9
7.4	166	78,925	3	.191	3.4	1.15	8.1	8.7	5	.110	6.0	1.20	4.9	11.5
2.8	62	29,529	2	.114	2.0	1.02	4.6	11.4	3	.064	3.9	1.29	3.0	16.3
.93	21	9,888	1	.071	1.3	1.28	3.0	15.1	2	.041	2.2	1.11	1.5	23.6
.37	8	3,964	1	.043	.76	.77	1.2	23.8	1	.024	1.3	1.34	1.2	35.0
.09	2	989	1	.023	.40	.40	.3	40.0	1	.013	.7	.70	.3	64.0

The Phase II engine module used in sizing E9 had a 15 ft^2 (1.39 m^2) capture area. When additional data on the permissible mass flow through the cored brick matrix heater became available (Reference 4), the mass flow per unit bed area was increased substantially. The module capture area, for the same size storage heater used in Phase II, has been increased to 27.6 ft^2 (2.56 m^2). This now represents a nearly full scale engine module for a potential operational hypersonic aircraft on the order of 600,000 lb (270,000 kg) weight, and increases the research capability of E9 substantially. The test section size for the scramjet module was determined using the following guidelines.



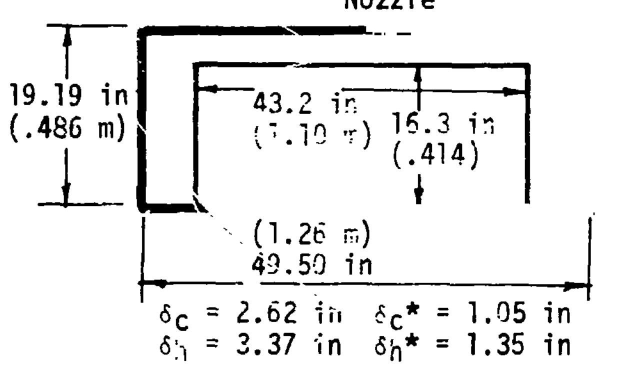
Where: δ_c is the maximum cold wall boundary layer thickness encountered in the nozzle for the range of conditions represented by the flight envelope of the potential operational hypersonic aircraft. δ_h is the hot wall boundary layer thickness, δ^* is the boundary layer displacement thickness.

By defining the maximum mass flow which can be accommodated, the maximum size nozzle potential flow area can be determined as a function of nozzle conditions. For E9, the maximum mass flow was selected at 550 lbm/sec (250 kg/sec) and a maximum potential core area was 800 in^2 (.515 m^2). The expression for potential flow area from the previous sketch is:

$$A_p = (h_{cowl} + 1.2\ \delta_c - \delta^*_h - \delta^*_c)\ (s_M + 2.4\ \delta_c - 2\ \delta^*_c)$$

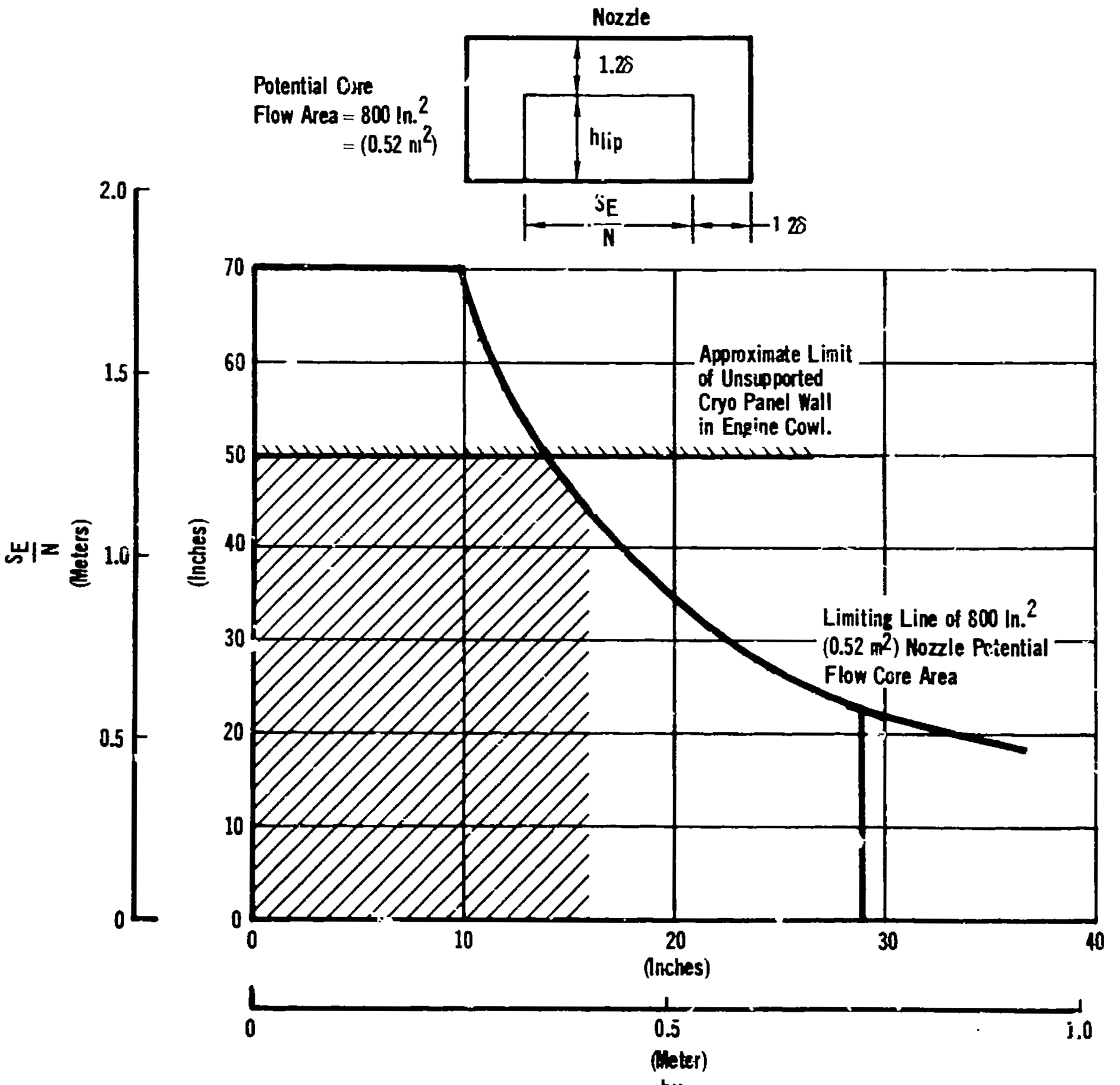
This yields a nozzle and module size of:

$A_{c\ Test\ Module} = 27.6\ ft^2\ (2.56\ m^2)$



This capability represents a significant increase in size over existing facility capability. The range of module sizes which can be accommodated by E9 and remain within the 800 in^2 (.515 m^2) nozzle potential flow core area is given in Figure 7-5.

FIGURE 7-5
RANGE OF MODULE SIZES WHICH CAN BE ACCOMMODATED BY FACILITY E9



Note: Shaded area indicates the limits of module size which can be installed in the flexible nozzle as specified. Taller or wider modules would require redesign of the test section.

The aerodynamic nozzles required for the thermo/structural research have been correspondingly increased in size and are shown in Figure 7-13. These represent a formidable capability, with nozzle diameters up to 19 feet (5.8 m) at Mach 12. Some of the model testing capability is indicated in Figure 7-13, which shows the representative models described in Figure 7-15 installed in the three nozzles.

By using information from AEDC and Fluidyne the definition of the zirconia heater was considerably improved. This improved definition should increase the credibility of the design and cost estimates, since it is based on the most recent data obtained at AEDC and incorporated into the TRIPITEE concept.

The carbon combustor concept has undergone considerable metamorphosis since Phase II. Because of the proprietary nature of the apparatus designed by Cabot Corporation which provides the fuel, only the combustion performance will be presented, in terms of effluent pressure, temperatures, and gas composition. Description of the apparatus associated with the carbon fuel supply and operation of the carbon combustor is not discussed in this report.

With the additional refinements in zirconia storage heater and carbon combustor performance the size of the engine module was increased to a capture area of 27.6 ft^2 (2.5 m^2) and the stagnation temperature capability increased to 7000°R (3900°K).

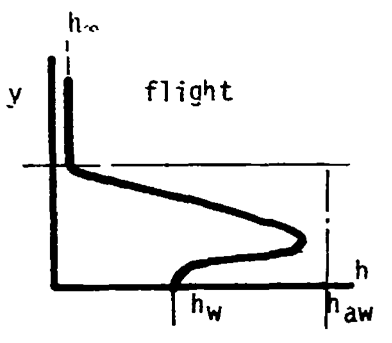
7.2 FACILITY DESCRIPTION AND COST

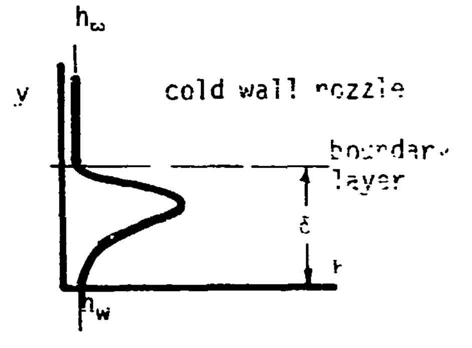
The scramjet engine research facility is subdivided into hardware elements to facilitate the discussion of component description, cost, and development assessment. The order of discussion is Scramjet test leg, Thermo structures test leg, continuous and intermittent heaters, compressor and exhauster plants and facility cooling system.

The scramjet test section, capable of providing conditions for both subsonic and supersonic combustion, is depicted in Figure 7-11, and as installed into the test leg in Figure 7-12. The alternate test leg arrangement with the thermo structural aerodynamic nozzles is shown in Figure 7-12 and 7-13.

For advanced dual-mode scramjets, a modified direct connect mode of testing was used. That is, the supersonic flow field upstream of the engine module cowl is duplicated in a variable Mach number nozzle system, permitting air flow through the engine modules as well as around three sides as discussed in Section 7.1, and shown in Figures 7-10 and 7-11.

In this simulation scheme, t' upstream supersonic flow and internal shock systems originating from the cowl lip are duplicated. The bottom wall of the nozzle represents the vehicle compression . , and the flow adjacent to this nozzle wall enters the engine module. ... onal nozzle wall cooling practice is followed, the enthalpy distribut... ll boundary layer would be so different from flight distributions the ... transfer and temperature would be greatly reduced. As depicted below, the enthalpy distribution would be substantially different for a cold wall nozzle compared to one characteristic of a hot walled aircraft.





The difference is due primarily to the large quantity of heat removed from the boundary layer in the process of cooling the throat. The concept of isentropic nozzle core flow with an adjacent boundary layer does not permit energy flow across the boundary layer, therefore the cold wall nozzle boundary layer has a much lower average enthalpy than a corresponding flight boundary layer.

In order to provide a similar temperature in the nozzle boundary layer entering the engine, the concept presented in Figures 7-10 and 7-11 was developed. The three walls of the nozzle, whose boundary layers do not enter the engine, are conventional backside, water film cooled walls. The bottom wall, whose boundary layer does enter the engine module, simulates the aircraft ramp structure and temperatures. The nozzle must be adjustable to provide duplication of the Mach number upstream of the cowl. To make this concept practical, the aerodynamic nozzle generating the flow was selected as an asymmetric, two-dimensional nozzle, providing one fixed wall. To provide a simple flexible nozzle concept, considering the modest Mach number requirements, a single jack flexible plate nozzle was employed (Reference 5). The fixed wall, opposite the flexible nozzle, is divided into three sections. The throat block region is constructed of refractory metal clad steel, which operates at a wall temperature of about 3000°R (1670°K). Some backside water film cooling is provided, as the heat transfer rate in the throat region would produce surface temperatures in excess of 3000°R without cooling. Downstream of the throat region, where the heat transfer reduces sharply to levels characteristic of the vehicle, the structure transitions into the insulated, refractory metal shingle structure typical of a potential operational vehicle. Depending on the engine design, somewhere upstream of the engine the insulated structure is terminated and a cryogenically cooled structure begins and continues into the engine module. The entire engine module is a cryogenically cooled structure. This concept then provides a realistic environment for the scramjet module in terms of boundary layer enthalpy distribution, surface condition, and aerothermodynamic conditions upstream of the engine cowl.

This design to accommodate cryogenically cooled engine modules is consistent with a developed engine design with an extensive base of experimental work. For development of basic concepts, water cooled "boilerplate" engine modules can be accommodated in the scramjet test section. This provides the necessary flexibility between low cost preliminary research and the more sophisticated arrangement necessary as finalized concepts are being developed.

The engine module is an operating piece of hardware, and is mounted on a thrust stand. The external flow and nozzle expansion contribute significantly to the thrust level. An attempt to provide some degree of exhaust simulation is reflected in the downstream concept of the scramjet test section. Most of the fuselage afterbody contour is provided as an expansion surface, downstream of the scramjet module exit. It is replaceable, so that different contours can be readily evaluated. The external flow velocity and static pressure should be relatively closely matched if reasonable exhaust expansion is to be achieved. To provide for this, a fixed contour, adjustable nozzle is provided on the upper wall, downstream of the cowl inlet. This expands the flow from the conditions just upstream of the engine to near free stream values. For example, for the trajectory point, Mach 10 at 110,000 feet (33.5 km), the required conditions are:

P_o = 12,500 psia (8,600 N/cm^2)

T_o = 6500°F (3610°K)

V_∞ = 10,002 ft/sec (3050 m/sec)

P_∞ = .125 psia (.086 N/cm^2)

M_∞ = 10

The modified direct connect conditions corresponding to the above trajectory point, and external flow field conditions which match external freestream pressure are:

P_o = 8700 psia (6000 N/cm^2)

T_o = 6500°R (3610°K)

V_∞ = 9730 ft/sec (2980 m/sec)

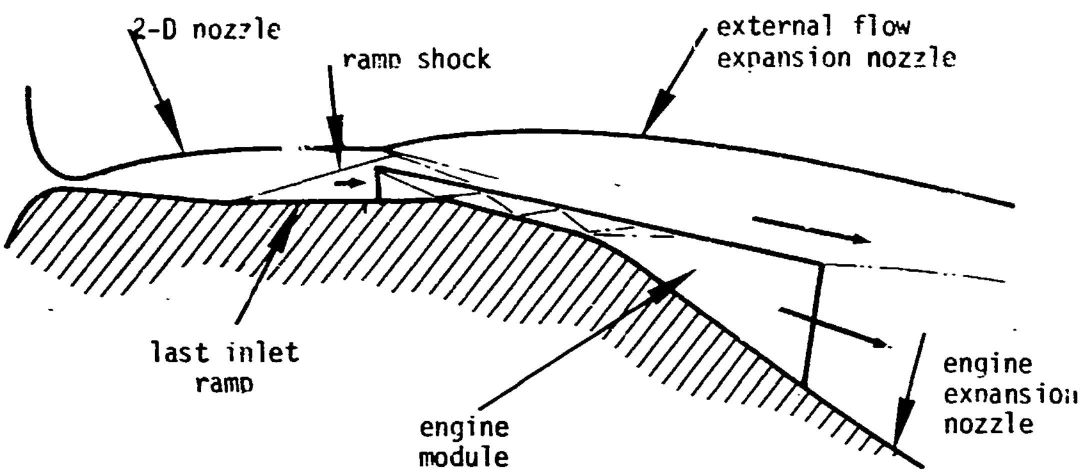
P_∞ = .125 psia (.0860 N/cm^2)

M_∞ = 9.5

External flow conditions closely approximating actual flight conditions can be provided by the modified direct connect test apparatus. The exhaust expansion is of course two-dimensional, being restrained from lateral expansion by the nozzle sidewalls. This is most valid for the engine modules in the center of a cluster, and least valid for the outer modules, resulting in a need to correct the measured thrust for lateral expansion.

As a whole, this scramjet engine test section provides a relatively close duplication of the inlet and exhaust conditions giving a reasonable basis for establishing module performance, cooling requirements, structural integrity and operational life.

One feature missing from this concept is the ramp shock system which can pass outside the cowl, impinge on the cowl lip, or enter the cowl. To simulate this, the nozzle system could be tilted, at a point where the shingled structure ends and the cryogenically cooled structure begins on the bottom wall as shown below. The resulting shock wave does not have the strength of three or four coalesced waves from the fuselage/inlet ramps, but an increment can be established for whatever the shock strength is. In this manner an additional degree of realism can be added to the simulated environment.



In Phase III the engine module size was re-examined and changed from the Phase II definition. The performance of the carbon combustion system was also increased by 17%. This necessitated establishing new performance limits for the equipment which comprised E9. The basis of the facility component description is summarized in Figures 7-2 and 7-6. The capability of E9 to supply the conditions necessary for flight duplication, consistent with the HYFAC potential operational aircraft, is shown in Figure 7-2. The various limitations imposed by technology and equipment selection judgements is shown. Figure 7-6a, b, c, translate Figure 7-2 into terms which can be used to specify hardware components, that is, pressure, temperature and mass flow. The relatively small compromise indicated by Zone (5) resulted in an acquisition cost decrease of about $90,417,000. As indicated by Figures 7-2 and 7-6, this compromise resulted in minimal reduction of the overall facility capability. These equipment deletions are such that, if required, their performance capability could be added later by doubling the compressor/exhauster plant, adding two more induction heaters, doubling the size of the oil fired heat exchanger and carbon system, and doubling the number of dehumidifying coolers. The heaters, compressors, exhausters, and coolers were sized based on the conditions shown in Figure 7-6.

The scope of the E9 facility is indicated in Figure 7-7 which shows a conceptual general arrangement of the complete facility. To indicate the interchangeability of the thermo/structural legs, an isometric view of both legs is shown in Figure 7-8. The legs are interchangeable from the heater exit to the facility supersonic diffuser exit. The addition of the aerodynamic nozzle capability adds significantly to the versatility and research value of E9.

FIGURE 7-6
INLET FLOW REQUIREMENTS FOR THE SCRAMJET MODULE, INCLUDING FACILITY LIMITS
a. Stagnation Pressure and Mass Flow

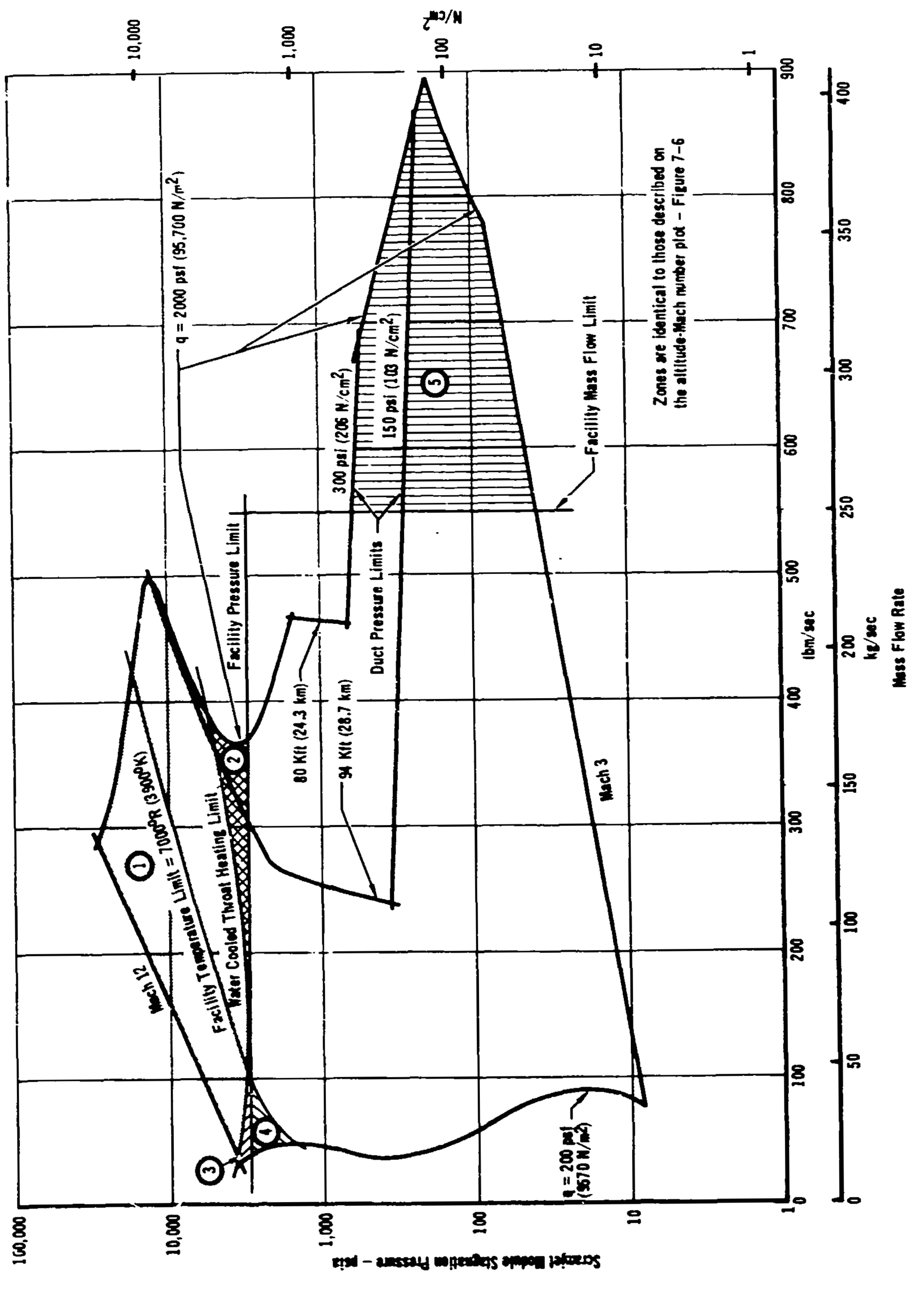


FIGURE 7-6 (Continued)
INLET FLOW REQUIREMENTS FOR THE SCRAMJET MODULE, INCLUDING FACILITY LIMITS
b. Stagnation Temperature and Mass Flow

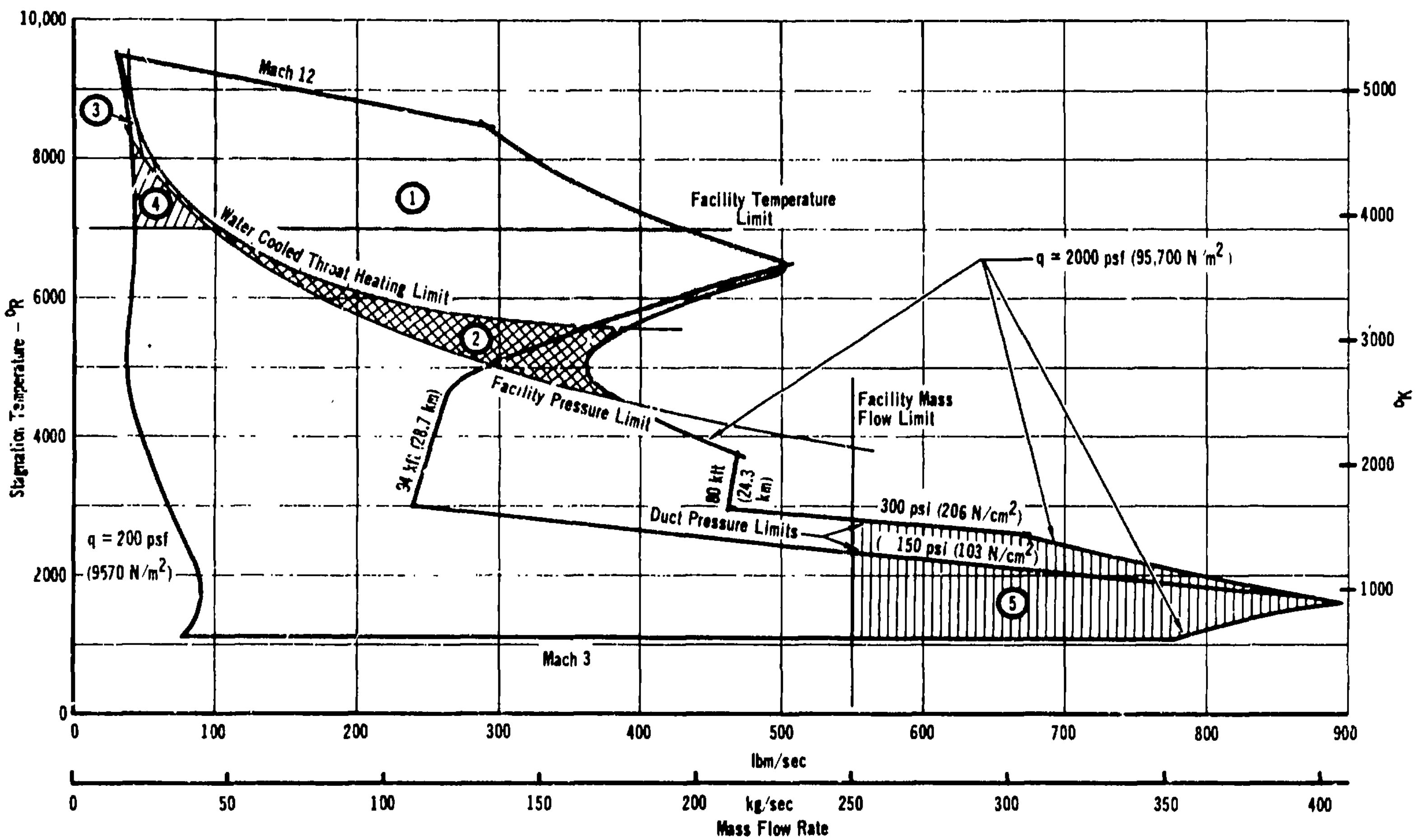


FIGURE 7-6 (Continued)
INLET FLOW REQUIREMENTS FOR THE SCRAMJET MODULE, INCLUDING FACILITY LIMITS
c. Stagnation Pressure and Temperature

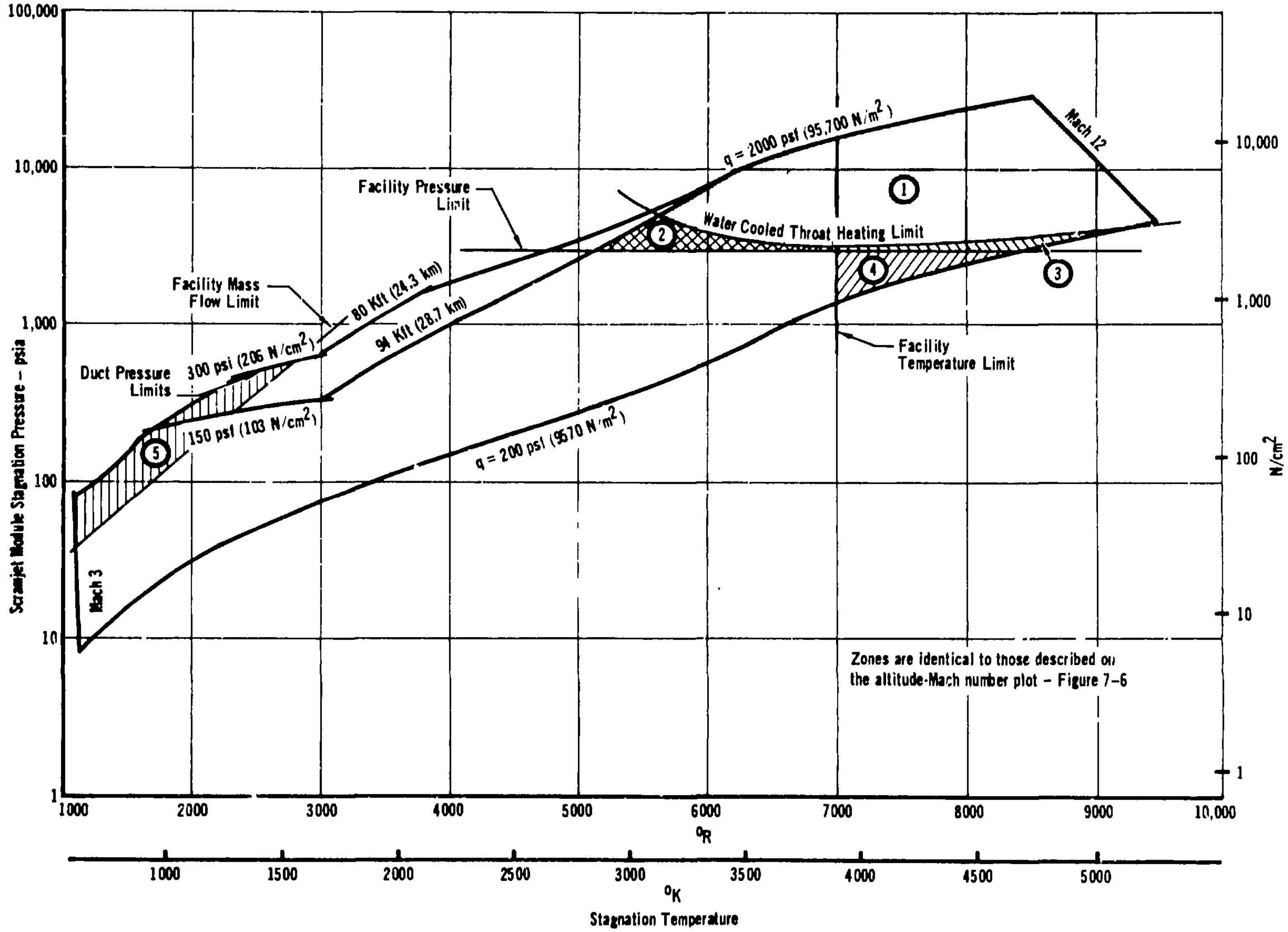
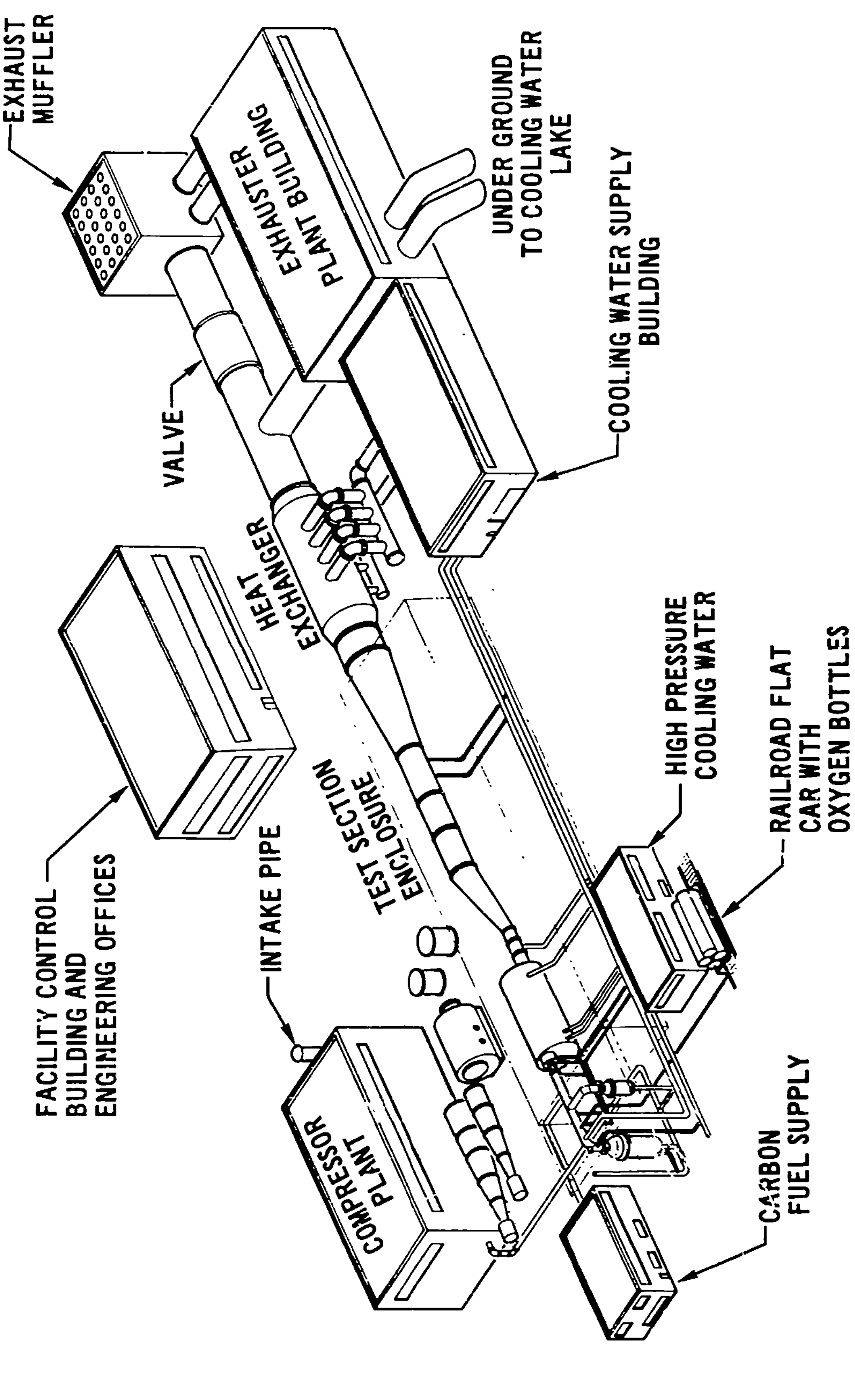


FIGURE 7-7
GENERAL ARRANGEMENT OF SCRAMJET ENGINE RESEARCH FACILITY (E9)



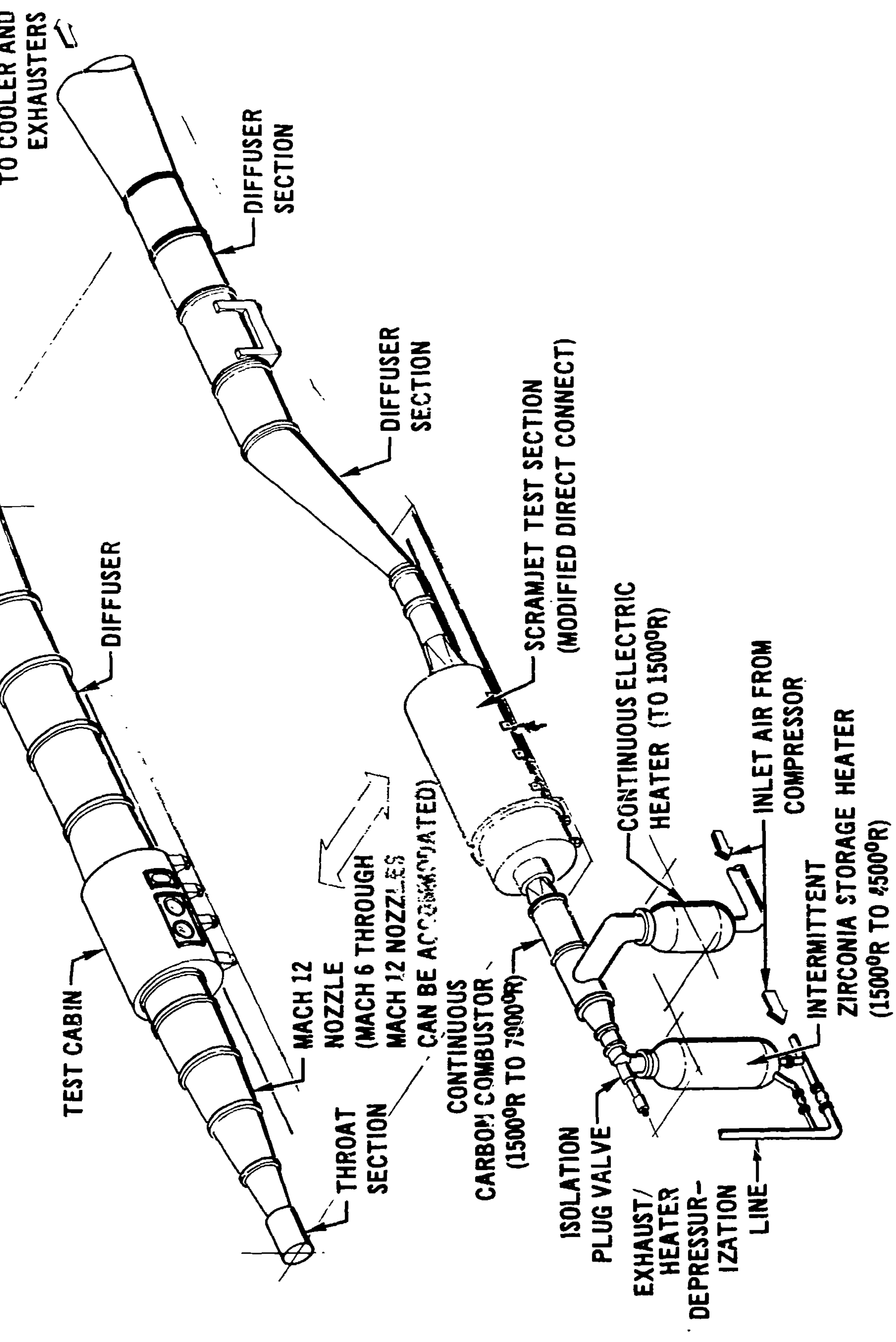


FIGURE 7-8
SCRAMJET LEG WITH INTERCHANGEABLE AEROTHERMODYNAMIC/ STRUCTURAL RESEARCH LEG

7.2.1 SCRAMJET TEST LEG - The concept of the scramjet test section is that a representative, two-dimensional slice through the inlet ramp, combustor, and exhaust nozzle can be made to generate a ground facility or flow system analogous to the aircraft flow field. The representation of this concept was shown in Figure 7-1. That portion of the aircraft comprising the facility, and the nozzle system confining the airflow to a similar streamline is indicated.

The scramjet module test section is shown in Figure 7-9 and consists of (1) a structural section housing an adjustable two-dimensional nozzle with one adjustable and one fixed wall; (2) the scramjet module, and (3) the exhaust expansion surface. The aft portion of the test section is supported on rails and can be moved away from the forward section for access to the test module. The aft movement is accomplished utilizing a downstream telescoping section in the diffuser. This same track is utilized to support and align the test cabins for nozzle tests in the thermo/structures test leg configuration.

The forward section of the test section is anchored and provides for facility thrust removal. The adjustable nozzle within this section allows variation of the inlet Mach number to the test module. This is a two-piece nozzle consisting of a water-cooled throat block and water-cooled flexible plate. The nozzle block which pivots at a fixed point is actuated utilizing a single jacking station. This block seals against the sidewall and at the forward portion of the support structure. The seals are located in and seal against water-cooled sections. One of the primary considerations in the design of this nozzle will be the pressure balancing of the water-cooling passages with the airstream.

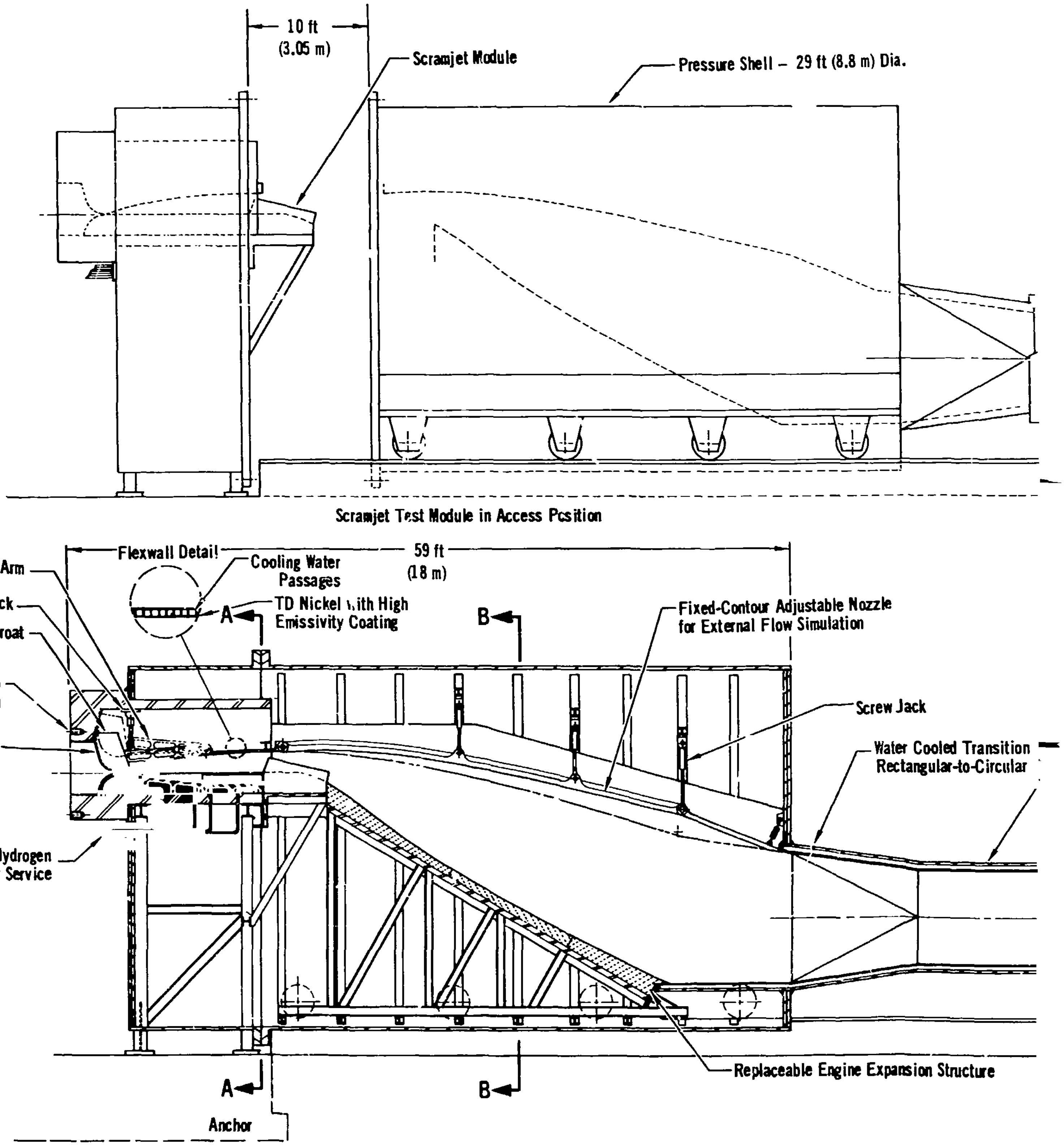
The flexible plate is a thin nickel structure incorporating rectangular water-cooling passages. The design and fabrication problems associated with this component will probably arise in the details of the water-cooling system connections and the controls required. The plate must have specific flexural characteristics and thickness distribution to provide the proper aerodynamic contour. Complicating this will be the requirement that the water pressure in the passages be matched to the airstream conditions to prevent deformation of the plate. A seal in the edge of the flexplate seals against the water-cooled sidewalls.

The lower nozzle block,which is stationary,is unique in that it is a hot wall structure simulating the flight vehicle surfaces and provides the proper scramjet module inlet boundary layer temperature conditions. The hot wall design details are shown in Figure 7-9. Basically, this nozzle is divided into three sections: a hot wall nozzle block, a radiation-cooled shingle structure, and a liquid hydrogen cryopanel structure.

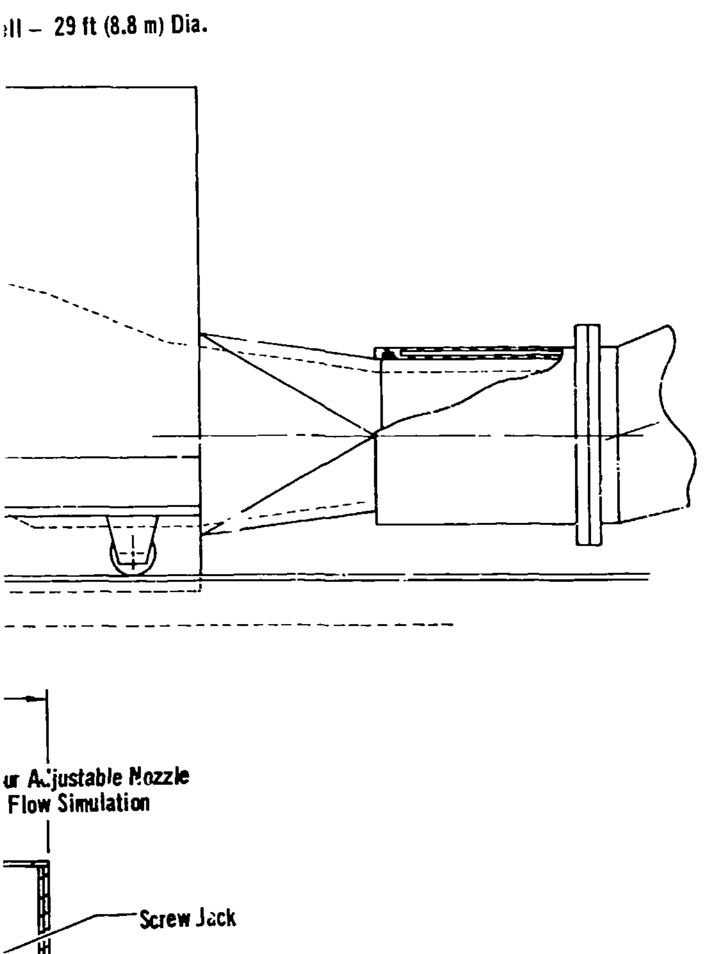
As shown in the drawing, the three sections of the lower fixed nozzle are water-cooled. The location of the water-cooling is dictated by the magnitude of the heat transfer rate and the desired surface conditions. A seal runs the length of the nozzle at the water-cooling location and seals against the water-cooled sidewalls of the support structure.

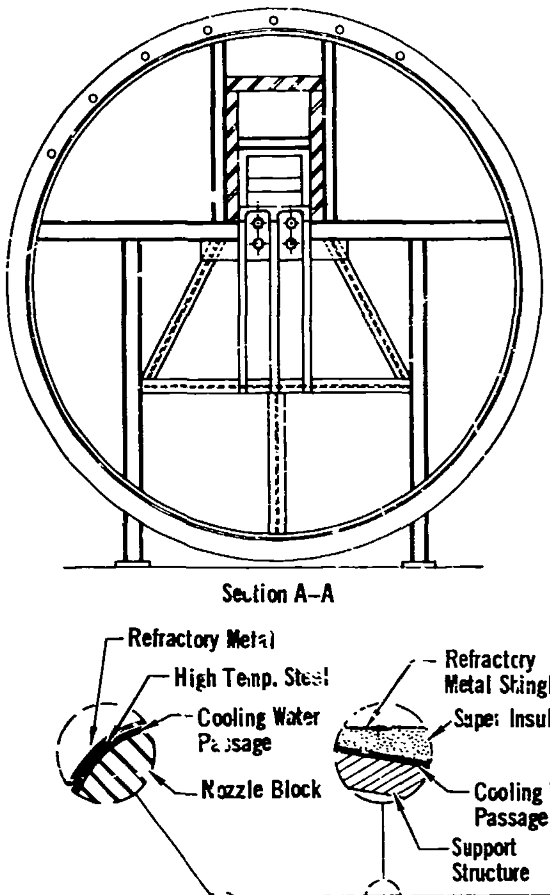
The fixed nozzle is fabricated from a water-cooled nickel substructure, clad with a thin sheet of T.D. nickel-chrome, columbium, or tantalum, depending on the full scale structure being simulated. Roll cladding of nickel with tantalum has already been accomplished and is commercially available. Cladding of chemically

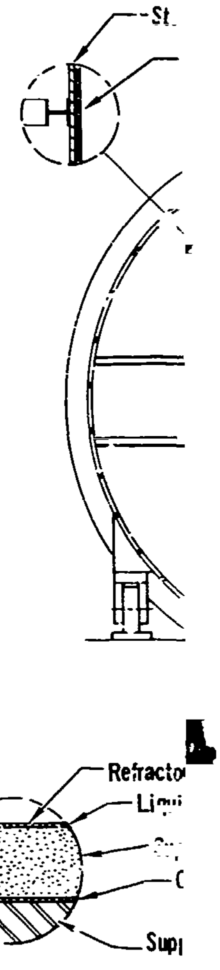
FIGURE 7-9
DUAL MODE RAMJET ENGINE RESEARCH FACILITY – SCRAMJET TEST MODULE

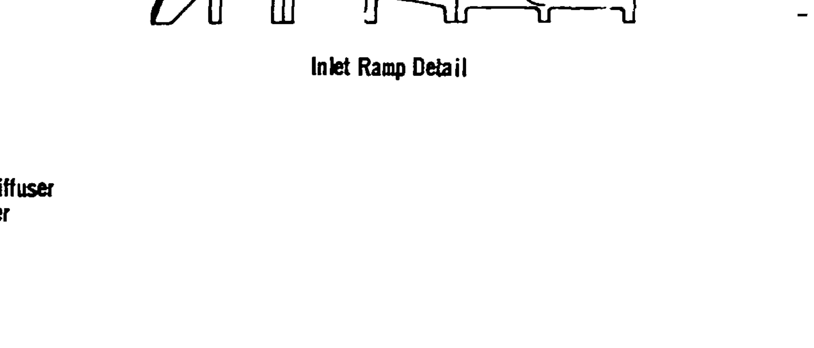


FOLDOUT FRAME 1

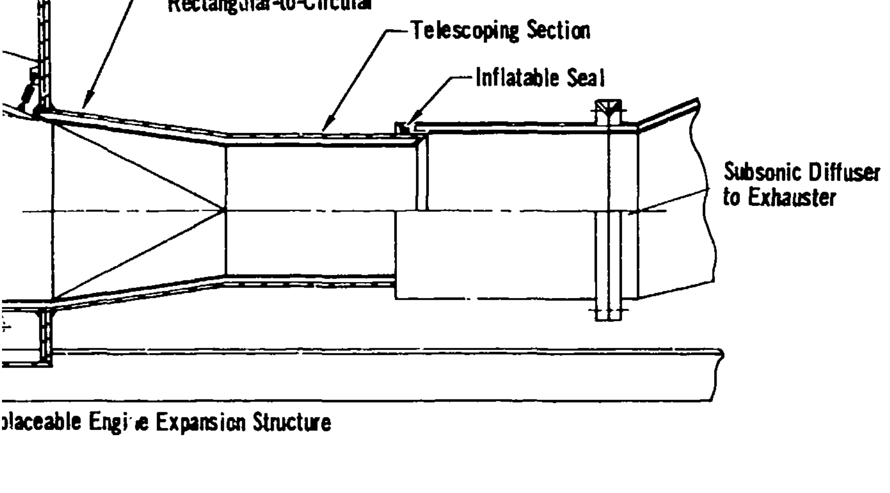



Section A–A



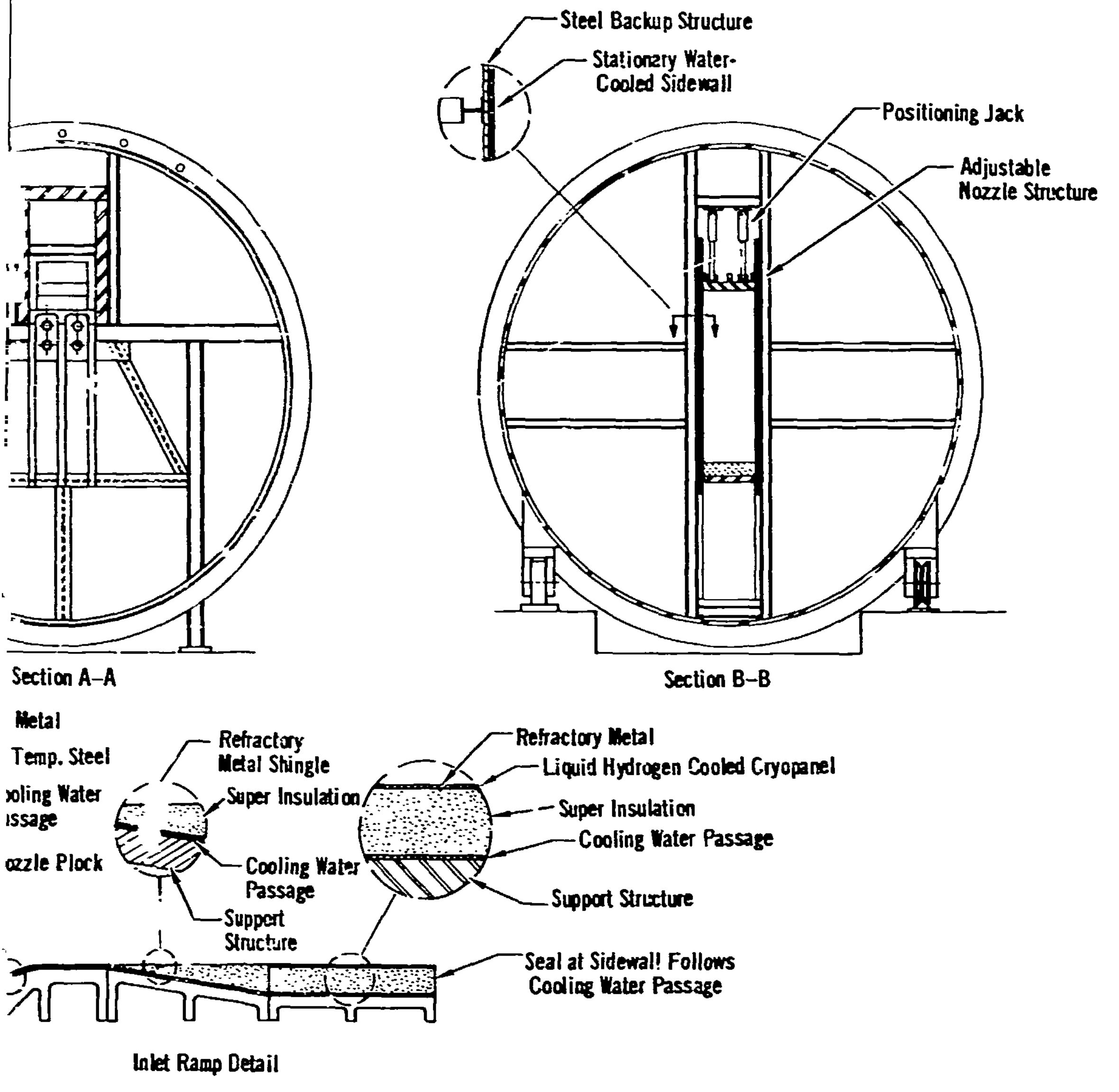


Inlet Ramp Detail



placeable Engine Expansion Structure

FOLDOUT FRAME 2



FOLDOUT FRAME

FOLDOUT FRAME 3

similar materials, like columbium to nickel, should possibly be based on the tantalum results. For use in air, the columbium and tantalum require an oxidation resistant cooling. Downstream of the fixed nozzle block, the actual aircraft material and structure are duplicated, with the insulation thickness appropriate for the local heat transfer rate, and desired surface temperature.

The design technology and fabrication techniques required to generate hardware of this nature are associated with aircraft manufacturing industries and not with wind tunnel fabrication technology. This hardware and the scramjet engine module, which is an operating cryogenically-cooled duct, will probably be fabricated in a model shop where the specific technology for fabrication exists or could be developed in a relatively short time. Since the lower nozzle and engine module configuration will change, there is a necessity to allow and build in flexibility in the test apparatus hardware in terms of support structure and services such as water, liquid hydrogen, electric and hydraulic power.

Initial operation with this module design need not require the use of liquid hydrogen cooled engine modules. In fact, with the water-cooling capacity provided, it is feasible to use boiler plate engine modules which are water-cooled and constructed from nickel or copper rather than refractory metals.

The sidewalls of the test module are back side water-cooled with a steel backup structure. The top and bottom walls and the sidewalls are structurally reinforced with a steel beam network which, in turn, is supported by the 29 foot (8.8 m) diameter pressure shell.

The engine expansion surface could be constructed in a manner similar to the actual operational aircraft. The flexibility available to change contours and evaluate different designs is limited, however. The concept shown is for a basic steel structure which can be coated with an air hardening, fiber reinforced ceramic mixture which could be readily recontoured and repaired. If the exhaust nozzle design has proceeded to specific definition stages, actual aircraft structure could be substituted for the low cost ceramic surface.

One of the primary operating problems to be encountered in the scramjet test apparatus will be the water and liquid hydrogen cooling requirements and their control. The coolant pressure levels may have to be balanced to the hot airstream to prevent structural damage to the thin wall cooling passages. In the nozzle region, the static pressure of the airstream will vary greatly over a relatively short span. This may require varying water pressures and/or water passage configuration within a single component. The water-cooling rate may also be required to change as the facility is brought from atmospheric conditions to the running flight condition. If this is the case, the cooling system must be programmed and interlocked into the flow control valve operation.

In a test apparatus of this nature where hydrogen is being burned, procedures for controlled operation must be developed to minimize the danger to equipment should failure occur. The hydrogen fuel control system must be interlocked to the facility run control to assure that the fuel system is at the proper rate and sequence. During inspection and equipment installation it may be desirable to empty and purge the liquid hydrogen system in the experimental apparatus. After a run,

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the test apparatus should be purged prior to allowing personnel in the working area. The engine module should be fitted with sensors to detect if the working area is free of toxic fumes or fuel.

The motor-driven jacks for the adjustable nozzle and fixed contour adjustable expansion plate should be incorporated into an interlock system which verifies the configuration prior to running.

To safely operate the test apparatus will require that temperature and pressure sensors be strategically located throughout the duct to monitor the various structural components. In addition, continuous monitoring of the cooling circuit conditons (both water and hydrogen) will be necessary to forewarn of impending over-temperature or pressure. These sensors should be interlocked to an alarm system and programmed into an emergency shutdown operation.

Another facet of the facility operation and control system which must be considered and programmed into the interlock system is the various kinds of emergency shutdown conditions. Depending upon the nature or circumstances of the emergency, certain equipment may require a number of shutdown control procedures. It will therefore be necessary to program the interlock system to handle more than a single emergency shutdown mode.

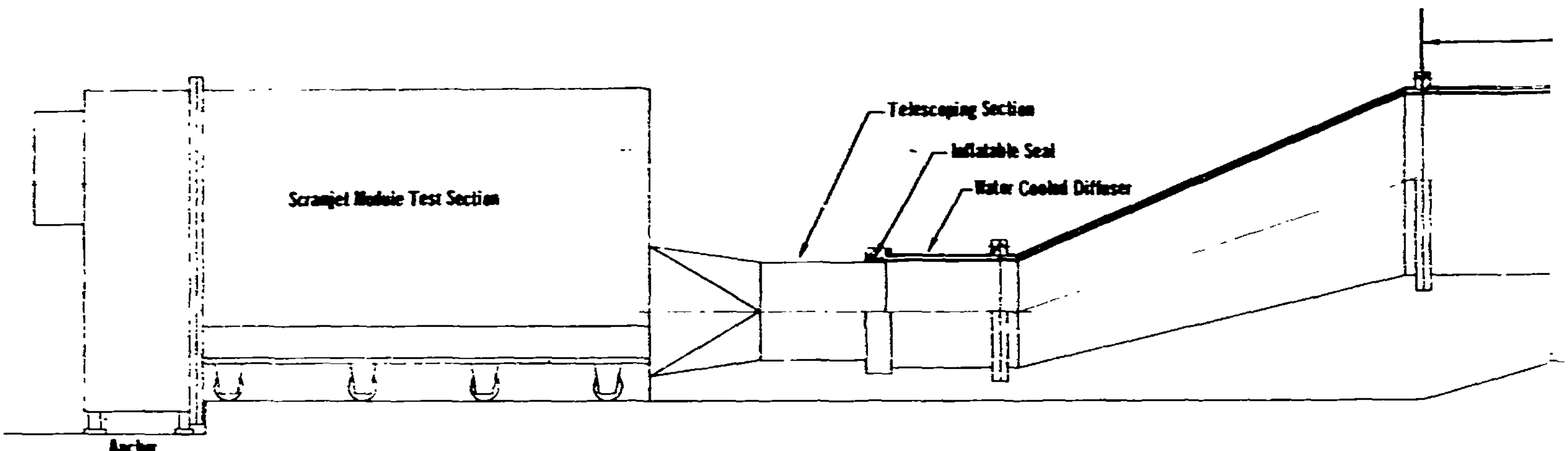
The split pressure shell is 29 feet (8.8 m) in diameter and the considerations associated with field fabrication are discussed in Section 2.0. Since there is personnel access to the scramjet module, the closure must be interlocked to prevent operation unless the shell is in the closed and secure position. Emergency shutdown switches must also be provided within the shell which will prevent operation if workmen are within the shell and provide emergency shutdown if necessary.

The exhaust ducting and diffusers for the scramjet test leg are shown in Figure 7-10. The scramjet facility exhausts on a centerline considerably below that of the inlet. To provide for the thermo structures test leg nozzles which attach to the combustor and utilize much of the downstream scramjet leg piping requires that the scramjet exhaust be elevated back to the common centerline. The commonality of the downstream piping can be seen in Figures 7-11 and 7-12.

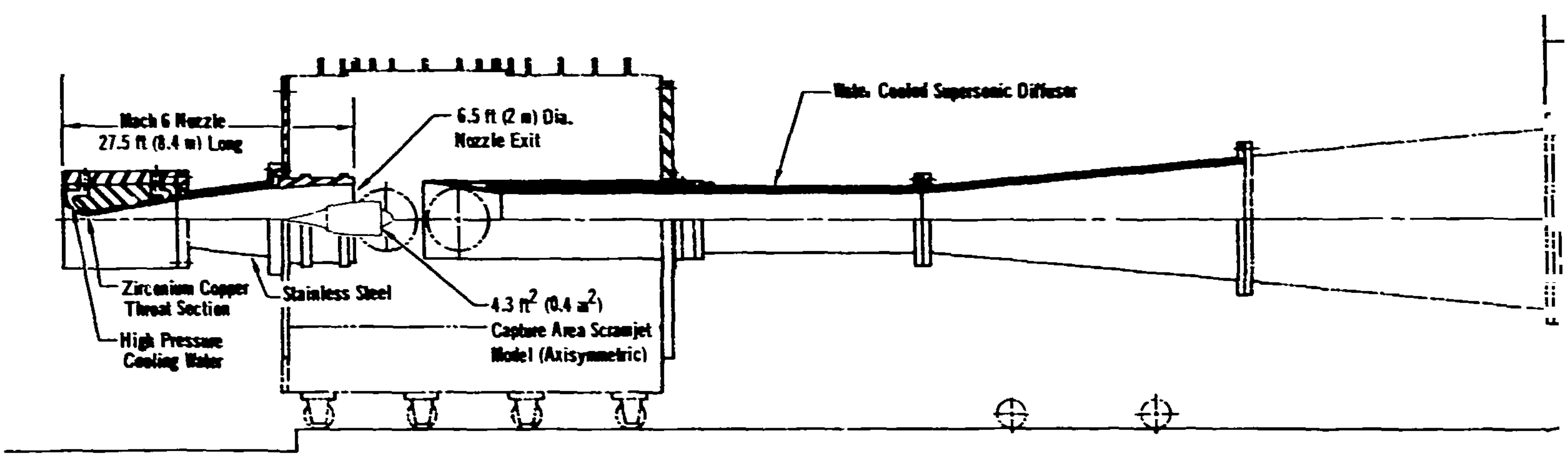
The downstream piping and diffuser sections are all water-cooled pipe sections of rather large diameter. These pipe sections are supported on cradles which run on tracks to allow for expansion and to provide facility alignment. Each of the piping sections, since they will be interchangeable, will either require individual water circuits and manifolds or provisions made to allow the water circuits of several sections to be put in series using matched water passages at flanges. The lengths of the various sections of piping will be controlled ultimately by whether the sections are field or shop fabricated.

The water cooling system for this piping will necessarily be quite large to handle and control the volumes of water required. The water control system will be a portion of the overall facility operation and will, therefore, be interlocked into the primary control sequence to assure that the cooling water system is in the proper configuration prior to initiating a run. Temperature sensors, cooling water flow rates, and pressure controls will be required to monitor and adjust the cooling

FIGURE 7-10
DUAL MODE RAMJET ENGINE RESEARCH FACILITY – TEST LEG ARRANGEMENT WITH SCRAMJET TEST MODULE INSTALLED – ALONG WITH INTERCHANGEABLE THERMO/STRUCTURAL LEG



Scramjet Module Test Leg



a. Mach 6 Nozzle Installation

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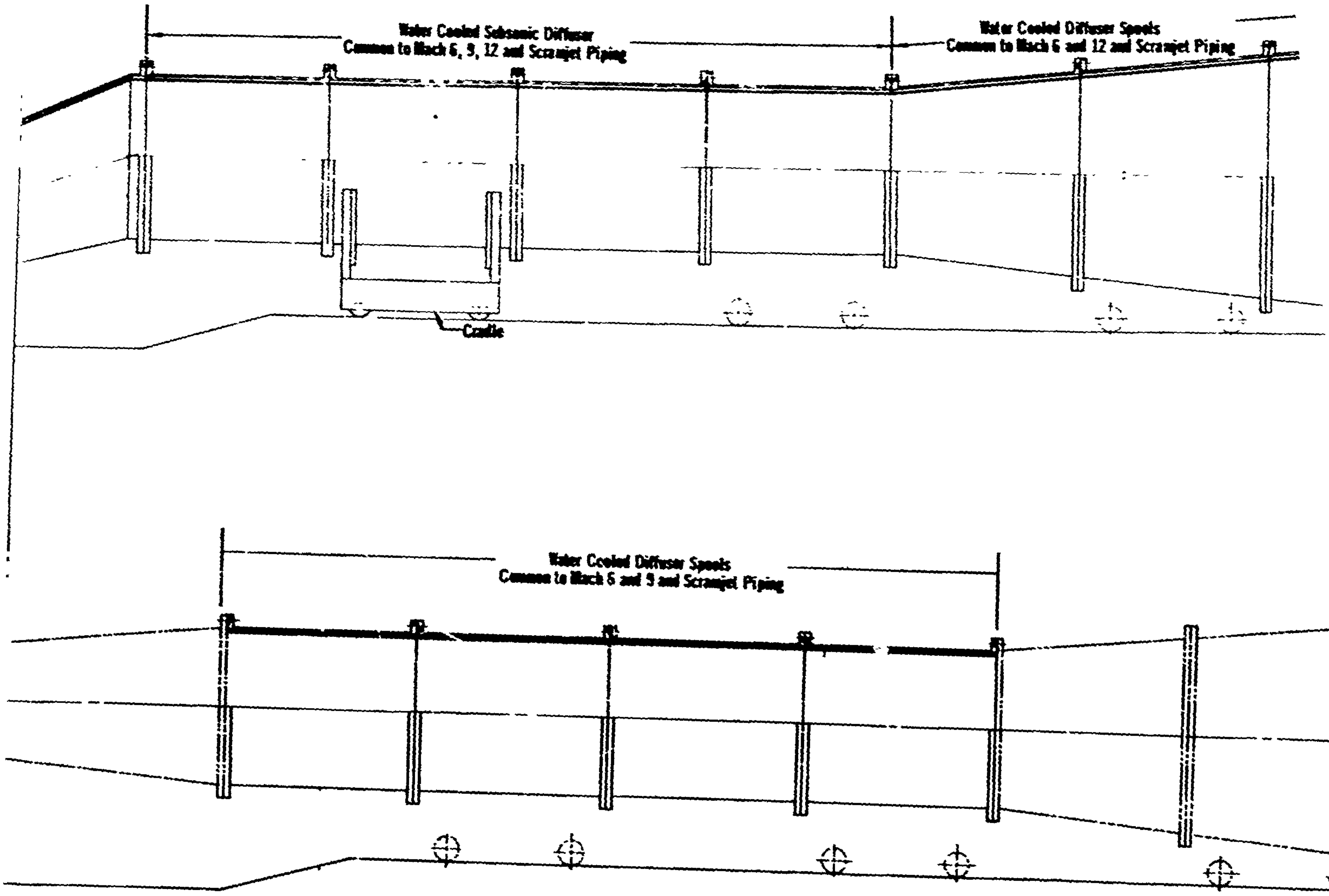

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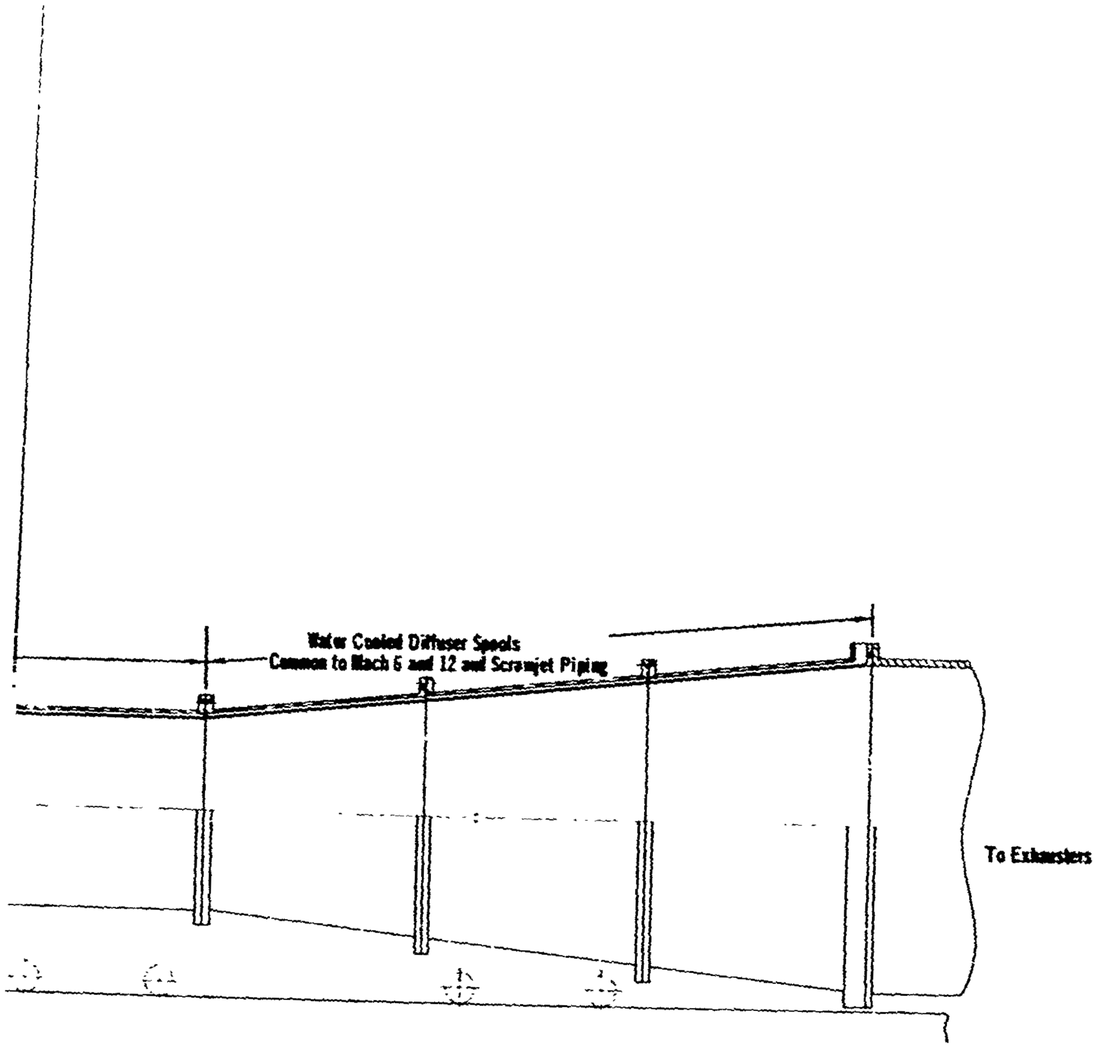

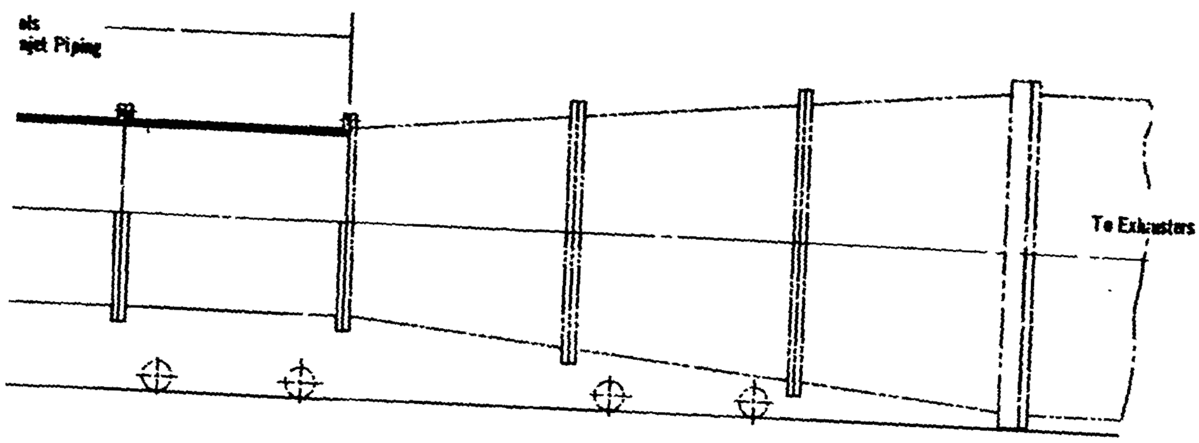

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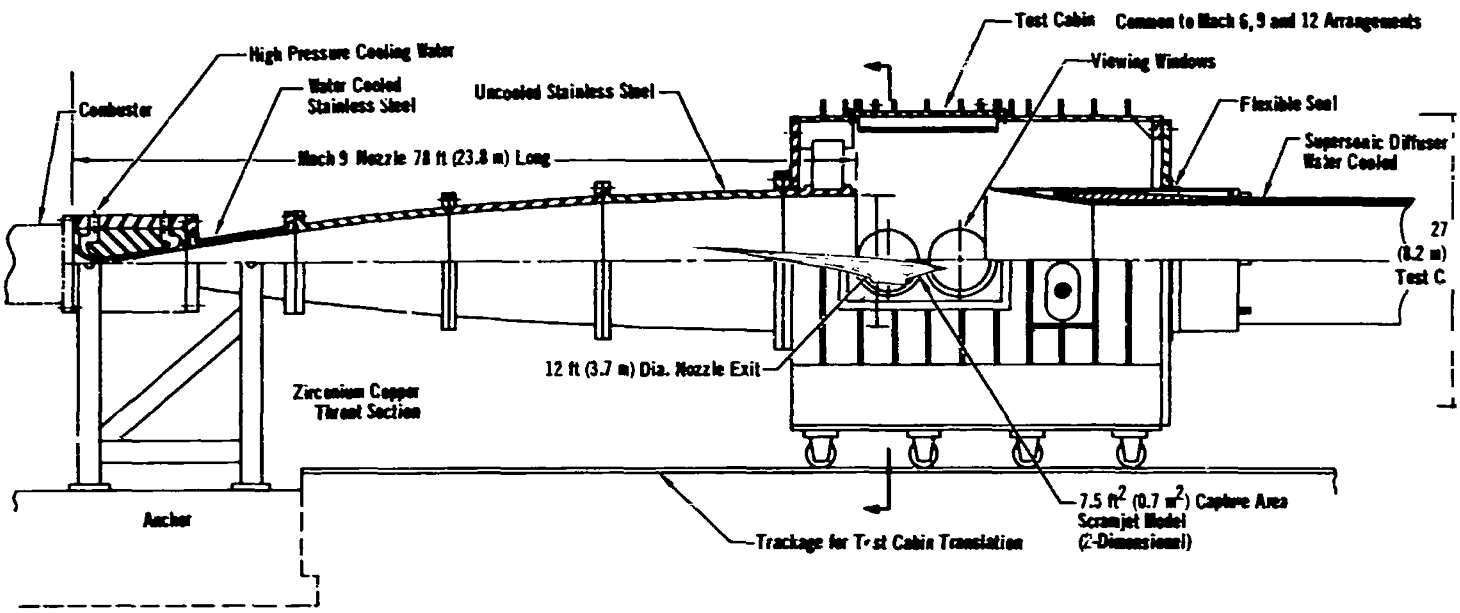
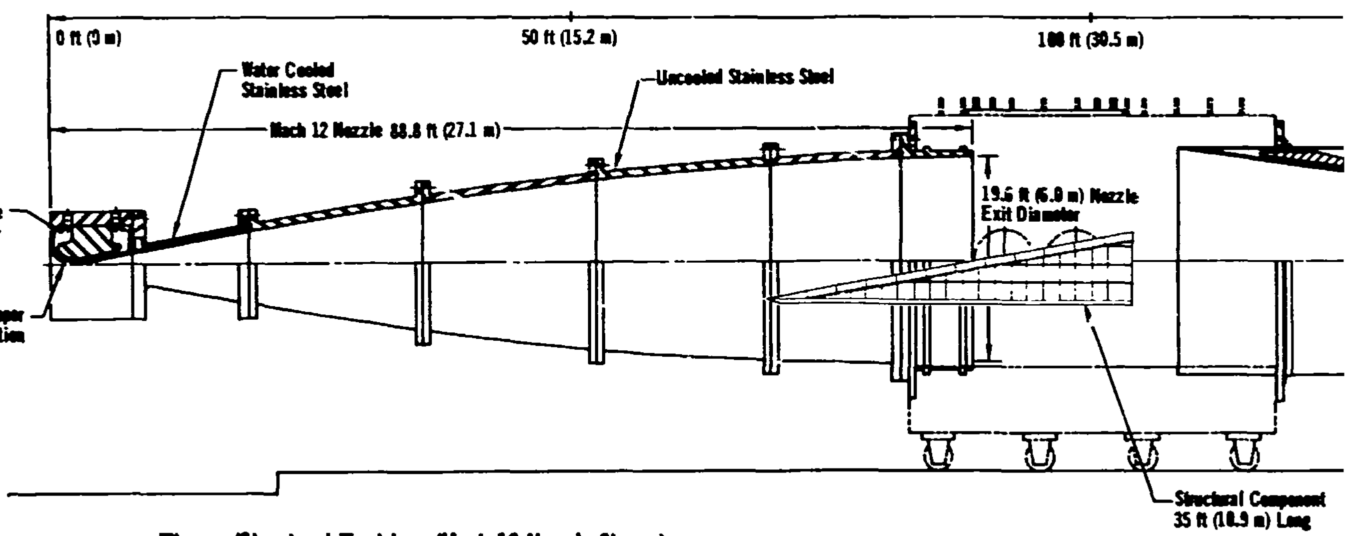


b. Mach 9 Nozzle Installation



c. Thermo/Structural Test Leg (Mach 12 Nozzle Shown)

FOLDOUT FRAME 1

7-30

DUAL MODE RAMJET ENGINE
WITH THERMOS

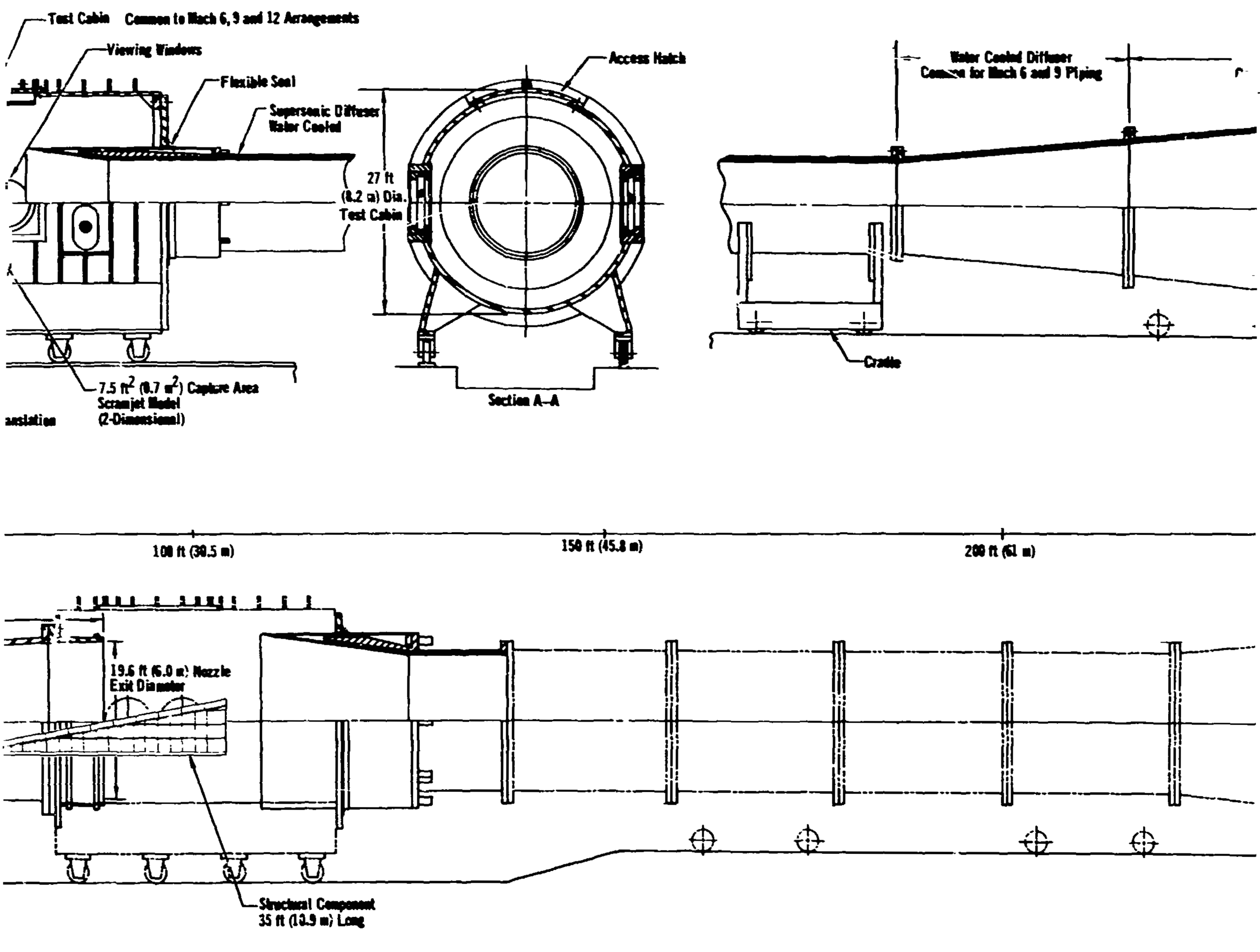


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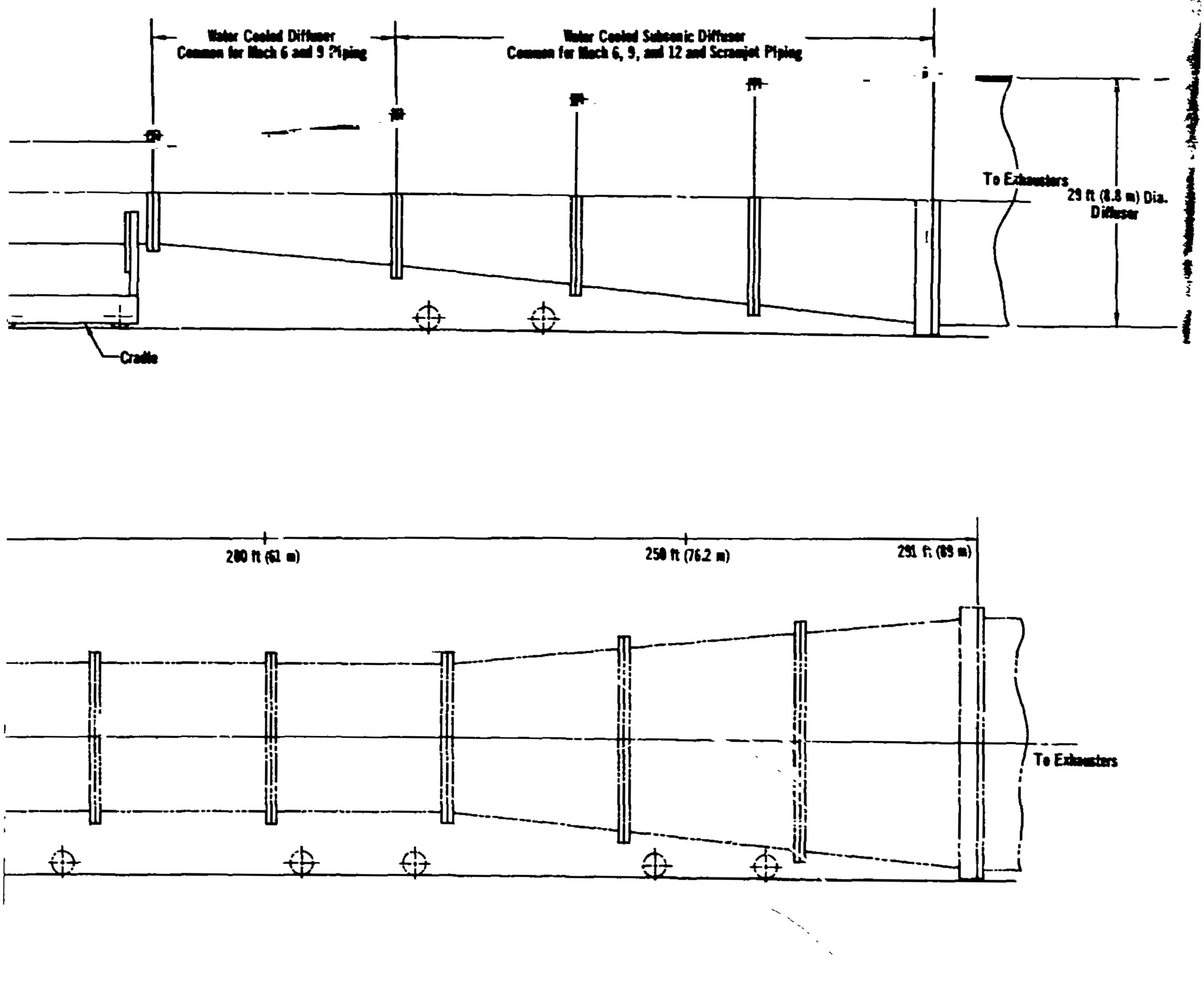
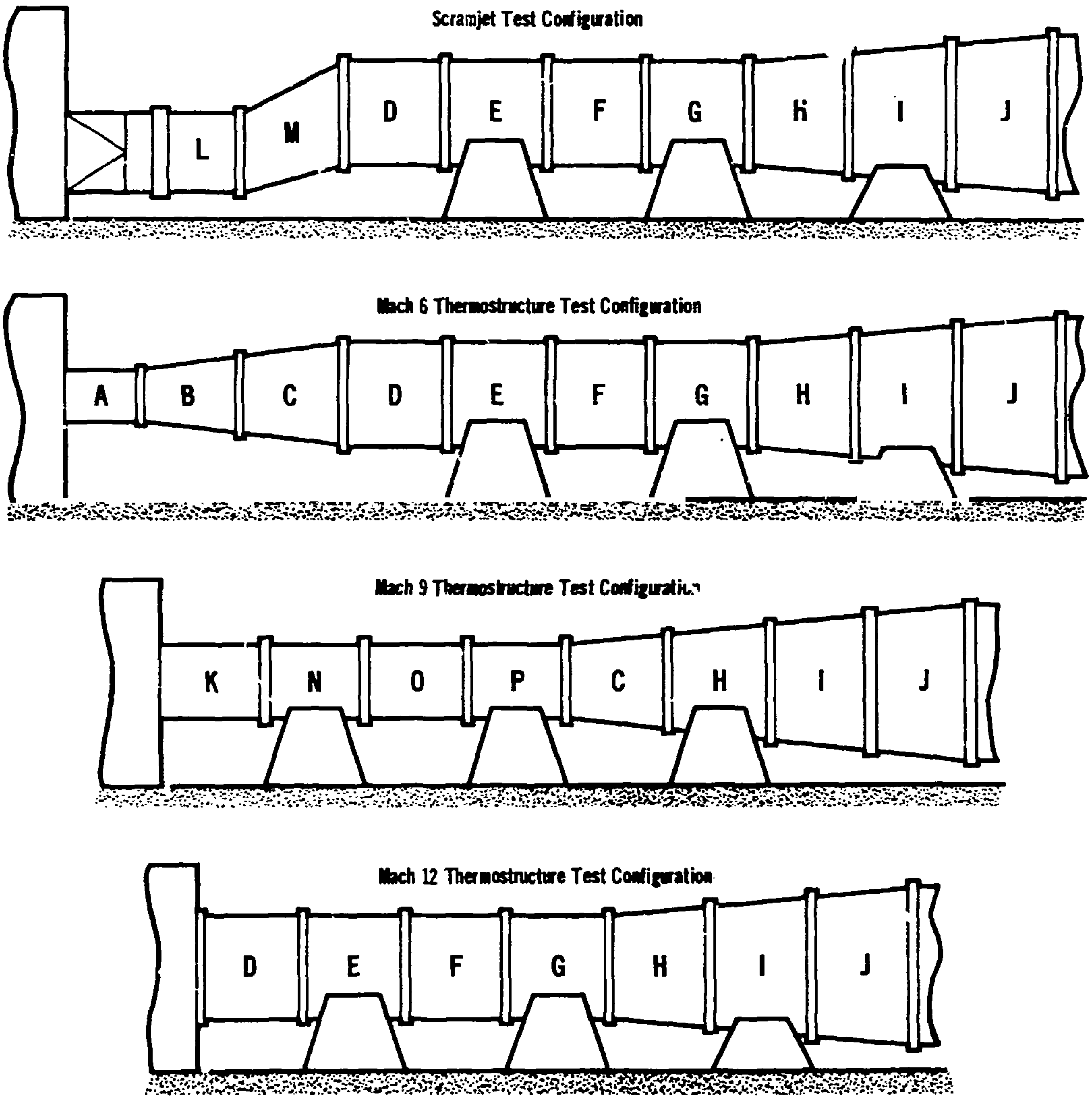
FIGURE 7-11
DUAL MODE RAMJET ENGINE RESEARCH FACILITY – TEST LEG ARRANGEMENT WITH THERMOSTRUCTURAL NOZZLES INSTALLED



FOLDOUT FRAME 3

FIGURE 7-12
DOWNSTREAM PIPING ELEMENT INTERCHANGEABILITY
TO ACCOMMODATE MULTIPLE TEST LEG ARRANGEMENT



requirements for each general section of the piping. Items such as water pump failure must be handled within a safety interlock system and any serious conditions would initiate facility shutdown.

Since the scramjet facility could discharge fuel (carbon based fuel or hydrogen) into the exhaust system, precautions should be taken to purge the piping after a run and consideration must be given to scrubbing the air to prevent possible damage or hazardous conditions from developing in the exhauster system.

The scramjet test module represents a relatively large structure embodying novel constructional and operational techniques. For this reason, a confidence level of 2 is assigned. Acquisition cost of the scramjet module is estimated to be $18,383,000.

7.2.2 THERMO STRUCTURES TEST LEGS - The engine facilities are the only flow facilities providing the capability of duplicating the actual flight environment, that is freestream pressure and temperature, and flight velocity. For this reason, these facilities provide the only source of data for thermodynamic research where both gas conditions and material temperatures are consistent with flight values, and are the only source of data on full scale structural components subjected to a duplicated flight environment with external flow. To provide this aerothermodynamic testing capability, aerodynamic nozzles are provided to generate these flow fields. A series of nozzles covering the Mach number range from 6 through 12 are represented in Figure 7-6. The throat areas correspond to that for the scramjet test section at the trajectory point of interest, and therefore have the same mass flow as required for the scramjet facility. The area ratio is for chemically imperfect gas flows as given in Reference (6). These potential flow contours were based on data obtained from Reference (7) and approximate the relative size for an actual nozzle. These nozzles are not the full theoretical length, but are shortened to the point where the last Mach wave intersects the boundary layer edge. The boundary layer corrections used for these nozzles are based on data obtained in the McDonnell Aircraft Company's Hypervelocity Impulse Tunnel, and are published in Reference (8).

Because the flight unit Reynolds number is duplicated, any model tests will be smaller than the full scale Reynolds number by the model scale. That is, a 2% model will have 2% of the full scale Reynolds number. However, for a full scale structural component, the local Reynolds number will be duplicated, as based on the dimensions of the component, for example, on full scale leading edge components the flight conditions and Reynolds number are duplicated.

The thermo structures test leg consists of three nozzle and piping arrangements. A common test cabin is utilized which is supported on the same trackage as the scramjet test apparatus. The thermo structures test leg arrangements are shown in Figure 7-11. The nozzle sizes are:

Nozzle Mach Number	Exit Diameter ft (m)	Constant Velocity Core Diameter ft (m)	Potential Flow Core Diameter ft (m)
6	6.45 (1.97)	5.7 (1.74)	6.0 (1.83)
9	12.2 (3.72)	8.8 (2.69)	10.8 (3.30)
12	18.6 (5.67)	9.0 (2.75)	14.7 (4.49)

Three axisymmetric nozzle arrangements are considered for this facility, Mach 6, 9, and 12. The throat regions of these nozzles have liners and are backside water cooled. The nozzles attach directly to the downstream end of the combustor. The nozzle throat sections of the nozzle are the most critical from a design and fabrication standpoint. These nozzles are very large and to provide the correct contours and machining tolerances necessary may require that each nozzle throat section (block and liner) be made in several sections to allow accurate machining. The water passages, which are formed by the space between the support block and the nozzle liner, also require accurate fabrication to assure the proper cooling passage dimensions which are necessary for adequate heat removal. The nozzle sections downstream from the throat area are not water cooled. Accurate machining and mating of the many sections will be necessary. The downstream ends of the nozzles extend into a free jet test cabin which houses the test specimens.

The primary operation and safety aspects of the nozzle test leg will be concerned with the integrity of the nozzle throat. Failure or burnout of the nozzle throat could suddenly increase the mass flow through the storage heater and either overstress the heater storage matrix (cored brick) or lift (float) the upper portion of the bed due to increased pressure differential. Either of the above cases would probably damage the refractory such that replacement would be required. The water cooling system for the nozzle throat section is, therefore, a critical item to be interlocked into the operational sequence. The nozzle throat cooling water should be backpressured to a level in excess of the airstream stati ssure. This will assure that in the case of a seal leak or failure of the liner that some water cooling is flowing into the critical area and that the hot high pressure air does not get into the water cooling system and damage the piping, controls or operating machinery.

The test cabin is a very large structural box which contains the test specimen. Being common to all of the test nozzles requires that the nozzle and diffuser ends have removable panels to allow r the size changes. An access hatch for test models is provided at the top and another for personnel in the side. Large windows are provided for viewing of the model.

Portions of the test cabin will be prefabricated. However, the final erection and fabrication will be required on site.

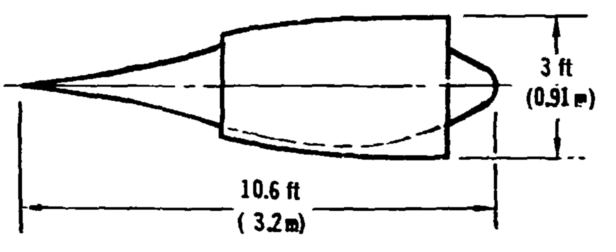
Three different supersonic diffuser arrangements will be required to install the three Mach number nozzles. The supersonic diffuser inlet sections will require design and fabrication techniques similar to those discussed for the axisymmetric water cooled nozzle section due to their relative complexity. The remainder of the water cooled supersonic diffuser piping and the large subsonic diffuser sections were previously discussed with respect to the scramjet test leg.

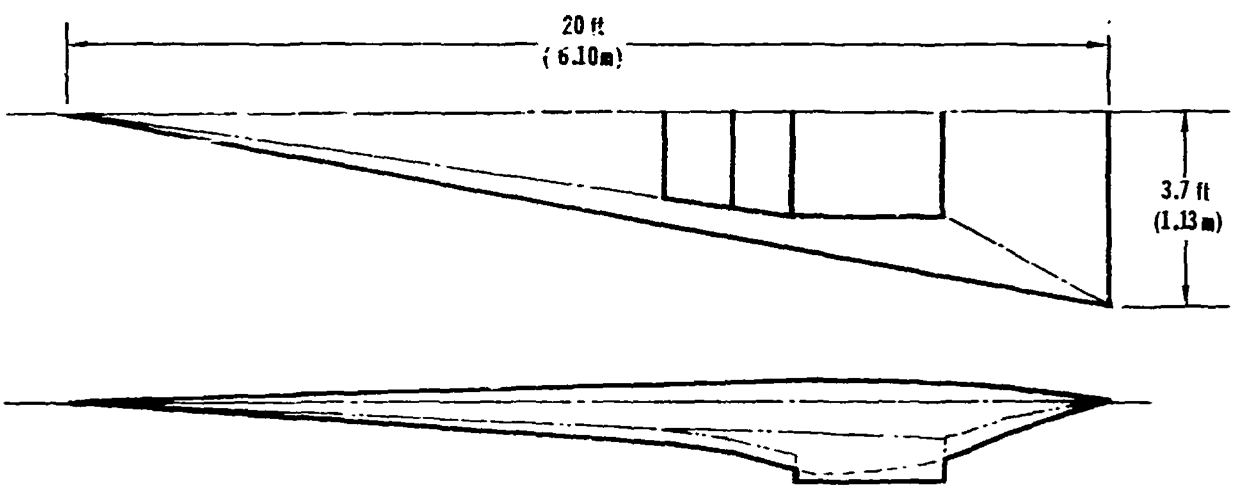
Emphasis should be placed on the flexibility which is incorporated into the downstream piping and subsonic diffuser arrangement (Figure 7-12). The use of interchangeable sections greatly increases the utility of the facility at a small increment in cost.

Three representative models which can be tested in the thermo structures nozzle systems are shown in Figure 7-13. Axisymmetric and integrated scramjet engines which could be free jet tested are shown in Figure 7-13a. Note that the same mass flow capability which can provide flight duplicated condition for a 27.6 ft^2

FIGURE 7-13a
THERMO/STRUCTURAL REPRESENTATIVE MODEL SIZES

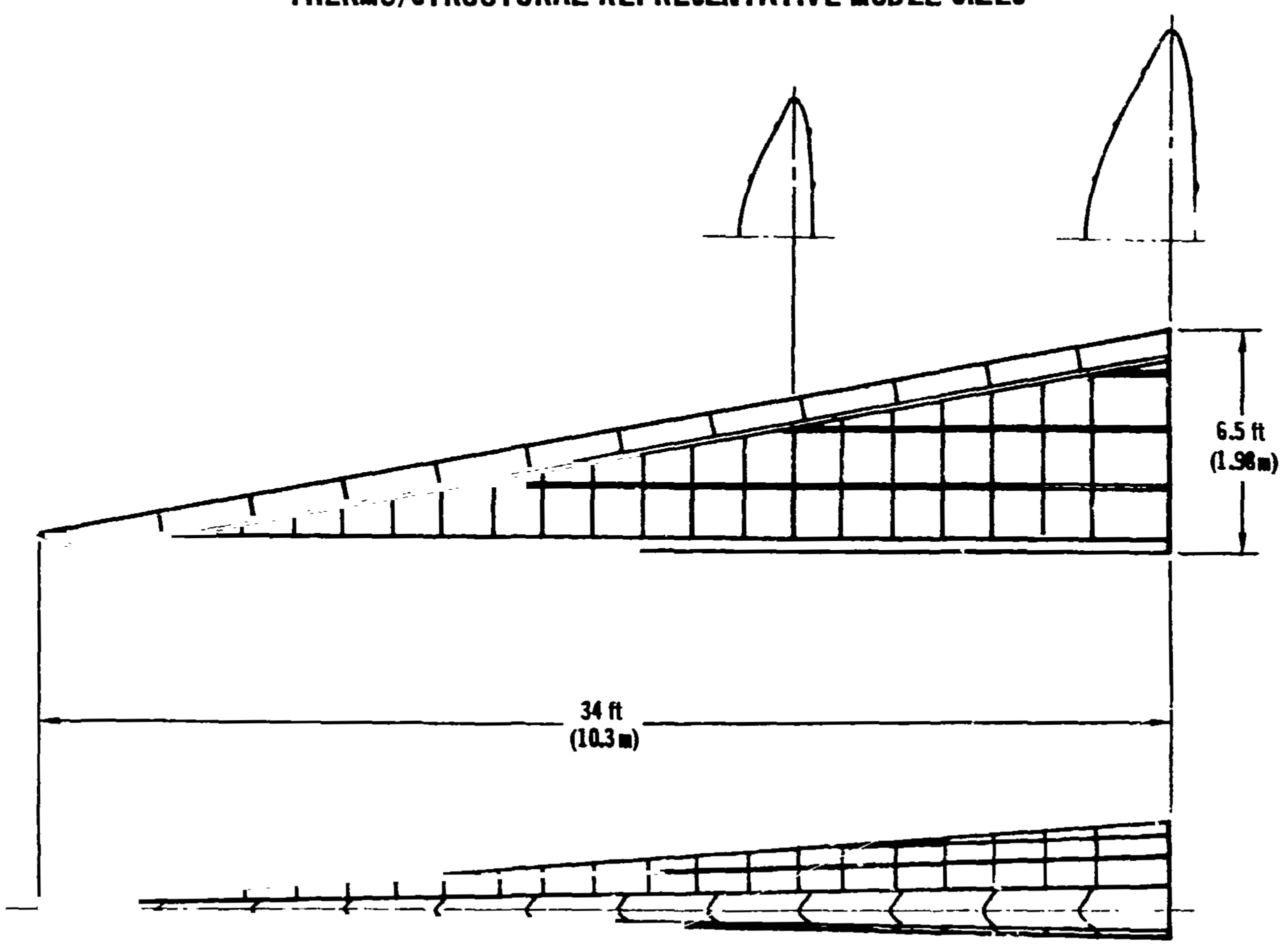
4.3 ft^2 (0.4 m^2) Capture Area, Mach 6
Axisymmetric Scramjet Engine
(Sized for Mach 6 Nozzle)





Mach 8, 3.7 ft^2 (0.34 m^2) Capture Area, Integrated Scramjet Engine
(Sized for Mach 8 Nozzle)

FIGURE 7-13b
THERMO/STRUCTURAL REPRESENTATIVE MODEL SIZES



110 ft^2 (10.2 m^2) Structural Section of a Hypersonic Aircraft
(Sized for Mach 12 Nozzle)

(2.58 m^2) capture area engine module using the modified direct connect mode, can only accommodate about a 3.5 ft^2 (.34 m^2) integrated scramjet engine for free jet testing. Thus, to accomplish what the modified direct connect test section does with 550 lb/sec (250 kg/sec (250 kg/sec) would require about 4300 lb/sec (1960 kg/sec) in a free jet facility. The size of a representative structural component is shown in Figure 7-13b. This size specimen represents the approximate current structures facility capacity to provide combined mechanical, thermal, altitude load simulation, and is a major increase in the size of structural specimens which can be accommodated in flow facilities.

This system provides the largest wind tunnel of its kind capable of flight duplicated conditions to Mach number 12. The cost of the nozzle and diffuser system is about 2.5 percent of the total facility cost, but increases its research flexibility and research value.

The thermo structural test leg is comprised of large, but conventional components. The fully contoured axisymmetric nozzles may require special construction techniques but the confidence level of the entire test leg is 4. Cost of the additional components which comprise this capability is estimated to be $6,347,000.

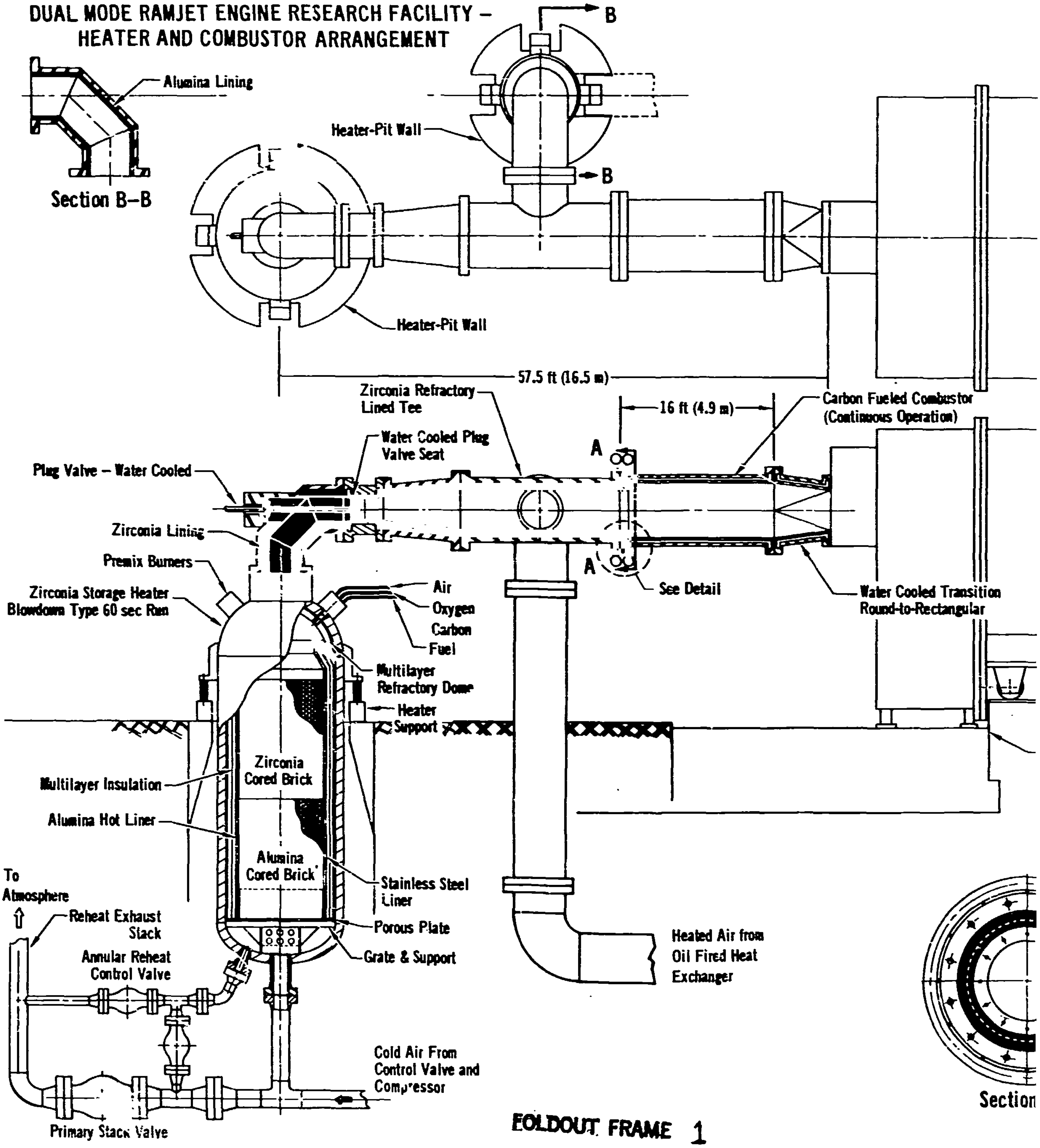
7.2.3 CONTINUOUS AND INTERMITTENT HEATER SYSTEMS - Two independent heater systems are required to satisfy the requirement for a long run-time scramjet test facility. In the continous operating mode, the facility is provided with high temperature and pressure vitiated air by a continuous heater system. This system consists of an air preheater and a combustor which uses carbon fuel, heated air, and oxygen. These heaters are used in series to provide true temperature capabilities up to Mach 10, and are used for thermal preconditioning of the engine module prior to taking pure air performance data in the intermittent mode, and for long run time experiments. The composition of the test gas using the continuous heater system is not identical to air at temperatures greater than 1500°R (830°K) but does maintain approximately 21% oxygen by volume at all temperatures and closely approximates the thermodynamic properties of air with low water vapor content.

In the intermittent mode of operation, a regenerative refractory heater is used to provide pure air at temperatures up to 4500°R, (2500°K) equivalent to true temperature operation at Mach 7.5 to 8.0. This cycle lasts for 1 or 2 minutes, depending on the run conditions. The storage heater can be cycled with the continous heater, providing the capability to obtain air performance data once every hour, reverting to vitiated air testing upon completion of the air cycle.

Figure 7-2 shows the flight corridor obtained by the facility and the regions of pure air and vitiated air testing. The following sections describe the features of both heater systems.

7.2.3.1 Regenerative Refractory Heater (Intermittent Mode) - The important features of this heater are shown in Figure 7-14. The heater is a pressure vessel filled with a heat storage matrix (bed). The bed is heated utilizing carbon fuel, air, and oxygen in premix, water cooled burners located at the top of the heater; the reheat gas is passed through the bed and exhausted from the bottom of the heater through an exhaust stack. Through proper design of the vessel insulation and control of the burner system, a variety of vertical temperature profiles can be produced in the matrix which allow predictable outlet gas temperatures during heater blowdown. Blowdown is accomplished by introducing cold air into the bottom of the heater and discharging it out the top into the ducting to the test section.

FIGURE 7-14
DUAL MODE RAMJET ENGINE RESEARCH FACILITY – HEATER AND COMBUSTOR ARRANGEMENT



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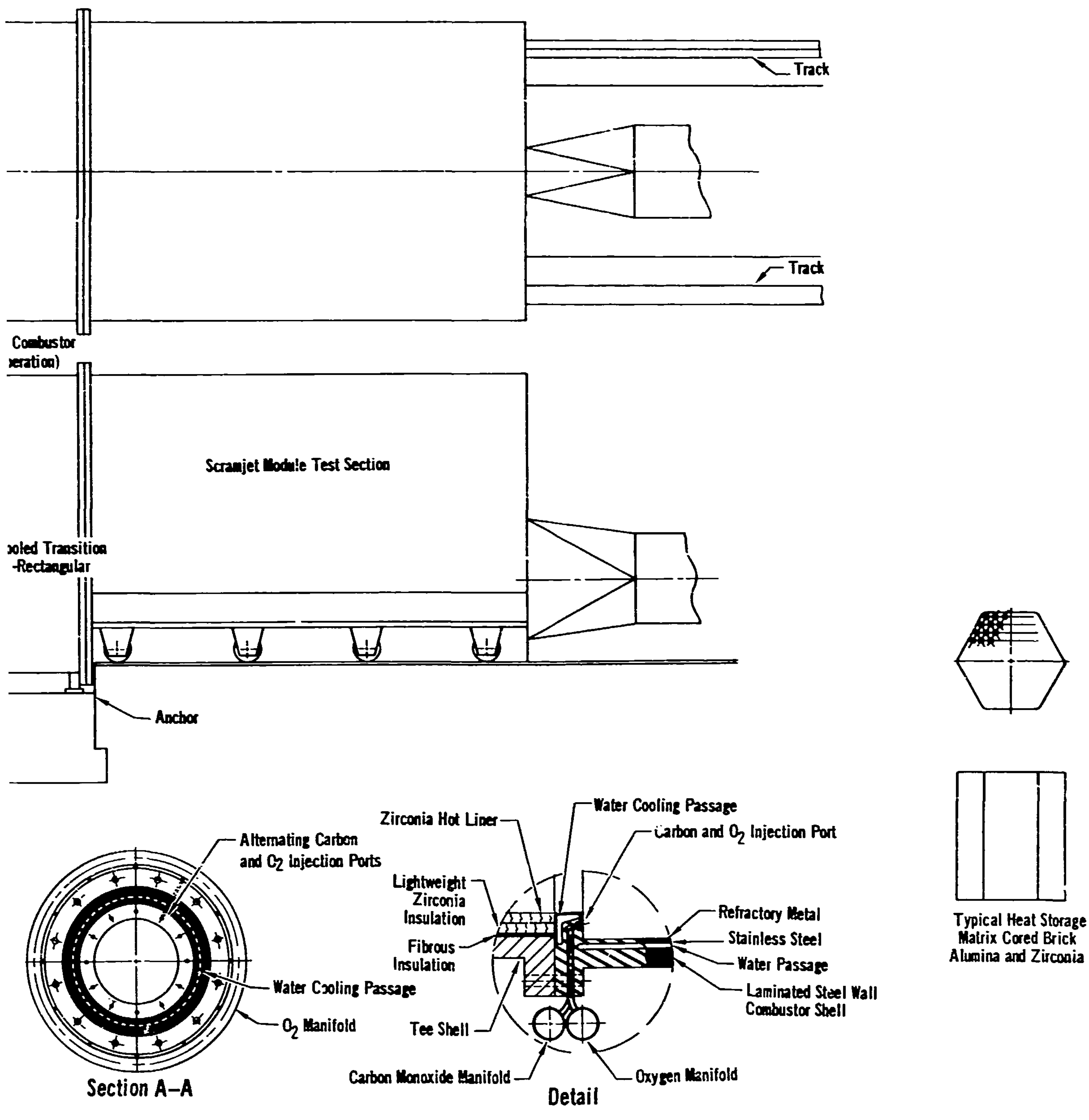

Track
Track
Combustor
eration)
Scramjet Module Test Section
ooled Transition
-Rectangular
Anchor
Alternating Carbon
and O_2 Injection Ports
Water Cooling Passage
O_2 Manifold
Section A–A
Zirconia Hot Liner
Water Cooling Passage
Carbon and O_2 Injection Port
Lightweight
Zirconia
Insulation
Fibrous
Insulation
Refractory Metal
Stainless Steel
Water Passage
Laminated Steel Wall
Combustor Shell
Tee Shell
Carbon Monoxide Manifold
Oxygen Manifold
Detail
Typical Heat Storage
Matrix Cored Brick
Alumina and Zirconia

The heat storage matrix for the heater will consist of zirconia and alumina cored brick for the upper and lower portions of the heater, respectively. The cored brick configuration and material specifications are determined from the mass flow rate, run duration, energy storage and heat extraction rate requirements, and the stresses imposed on the brick. The bed is supported from the bottom of the heater on a grate support system. To assist in the formation of the proper bed temperature profile and to prevent overheating of the grate or vessel, the heater including the matrix, is fitted with thermocouples.

The complete heater system is supported from the side of the vessel and suspended in a pit. The support system allows for thermal growth such that the centerline of the facility will remain fixed.

The most critical item in the storage heater system from an operational standpoint is the reheat system. The reheat system must incorporate a complete set of controls (pressure regulators, flowmeters, valving, etc.) for each of the combustion constitutuents. To avoid damage to the refractory material, specific heating procedures must be established. The heater matrix vertical temperature profile must be formed in steps to prevent excessive stress levels from occurring in the cored brick and to prevent over-temperature of certain portions of the heater before the desired maximum bed temperature is achieved. Burner operating tables or reheat schedules must be prepared generally for each of the desired heater outlet air temperature levels. These schedules describe the burner flow rate requirement for each of the combustion constituents (carbon, air and O_2) and the length of time at the particular burner setting. In addition, the reheat schedules and the operating procedures set forth will assure oxygen-rich operation and prevent damage which can be caused by burner flashback or blowoff. The burner operator is aided in the reheat process by thermocouple instrumentation throughout the bed.

In large diameter heaters, an additional feature is incorporated into the reheat system to reduce the radial temperature profile caused by heat loss to the insulation and vessel walls. This radial profile, hotter in the center of the matrix than around the periphery, will cause a reduction in heater outlet temperature if uncorrected. In addition, the radial profile introduces severe temperature gradients in the cored brick near the insulation and may become serious enough to cause cracking of the brick. To reduce the radial temperature profile, annular reheating is utilized which consists of forcing the reheat gases to flow annularly through the matrix, i.e., ideally no flow through the center section of the matrix. This is accomplished by designing the grate system to allow reheat flow in two separate areas. The annular reheat gas is taken out of the heater to the exhaust stack through a separate line.

During reheat, safety precautions are required to prevent personnel or facility component damage. Prior to burner ignition, the burner and heater must be in the proper configuration. The proper configuration would include:

- o Desired exhaust valve positioning.
- o Plug valve at heater outlet closed and locked.
- o Plug valve cooling water on and flow rate set.
- o Burner cooling water on and flow rate set.
- o Burner controls in proper positon.
- o Burner air, O_2 and carbon fuel supply flow rates set.
- o Thermocouple recorders on.

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The reheat system must incorporate an interlock warning system which indicates such items as over-temperature or loss of burner or plug valve cooling water. Interlocks on the burner control system would prevent burner operation if any of the above tasks were not accomplished, During burner operation, loss of cooling water, indications of burner flashback, or loss of one of the burner combustion constituents would shut the burner off and sound an alarm.

Prior to blowdown operation, the refractory heater system must be secured for safe operation. Specific tasks and system checks will be required which will be interlocked items and are listed below.

1. Burners secured for blowdown operation
   - o Water cooling conditions (pressure and flow rate) set
   - o High pressure isolation valves on combustion constituents closed
   - o Purge air for burner(s) set

2. Heater in blowdown configuration
   - o Heater temperature profile confirmed
   - o Primary stack valve closed
   - o Annular reheat valve closed and blowdown valve open
   - o Recorders on for monitoring heater temperatures

During the actual blowdown, specific items will be monitored and interlocked to prevent heater system damage, such as pressure across heater bed, heater pressure, and certain vessel and refractory temperatures. Exceeding predetermined limits on these items would initiate shutdown.

A refractory lined elbow passes the hot air flow from the heater to the facility ducting. Incorporated into this elbow is a plug valve which isolates this storage heater from the air preheater and combustor ducting. A water-cooled pipe section connected to the downstream end of the elbow provides the plug valve seat. The plug valve, when fully retracted, is housed in a cavity out of the hot air stream. Provisions will be required in the design to allow frequent inspection and maintenance of the plug and seat items.

The plug actuation system must be automatically controlled, utilizing a programmed interlock system to assure proper sequencing of the plug valve with the continuous operational mode pressure control valving. A failsafe system for facility control valve operation is essential in case of power failure. Various areas of the elbow shell, refractory lining, and plug seat will require interlocked thermocouple instrumentation to prevent overheating of these components. The plug valve and seat contain separate water systems which must be interlocked to prevent burner, blowdown, or continuous mode operation prior to establishing the proper water cooling conditions. In case of water system failure, the facility operation would be shut down.

A manifold and tee piping arrangement is included in the piping to provide entrance ducting from the continuous air preheater. This high pressure piping is internally insulated with a refractory lining capable of withstanding the maximum temperature capability of the storage heater. The manifold and tee arrangement will be instrumented with thermocouples and interlocked to prevent overheating. Special design or fabrication problems are not anticipated. A means of visual inspection of the refractory lining should be provided. This could be accomplished by providing view ports at several locations.

The combustor is connected directly to the pipe tee and for blowdown operation of the storage heater is used only as a stilling chamber or duct to the scramjet module or thermostructures nozzle arrangement. The details of this item will be covered later in the text during discussion of the continuous operation.

A summary of the important specifications of the regenerative heater follow:

Type	Zirconia/Alumina cored brick matrix storage heater
Reheat system	Carbon fuel, air, oxygen
Max. mass flow	550 lbm/sec (250 kg/sec)
Max. pressure	3000 psi (2070 N/cm^2)
Max. temperature	4500°R (2500°R)

Refractory storage heater design, including material specification, fabrication, and operation, have advanced significantly in the past few years to the point where development work in materials or fabrication is not anticipated.

The refractory lining of the elbow will require the design and fabrication of special shapes which are currently within the abilities of refactory manufacturers. No special problems are anticipated in regards to material selection for this item.

Plug valves of the specified type have been operated in a similar environment on a much smaller scale. Some development may be required on this item to provide the necessary transfer of technology. The assigned confidence level of the regenerative heater, associated ducting, and reheat system is 4. Estimated cost of the system is $7,189,000.

7.2.3.2 Continuous Heaters - The continuous mode of operation utilizes the air preheater in series with the carbon combustor to generate the desired flow conditions. During continuous operation, the plug valve isolates the refractory storage heater which may be in a reheat cycle.

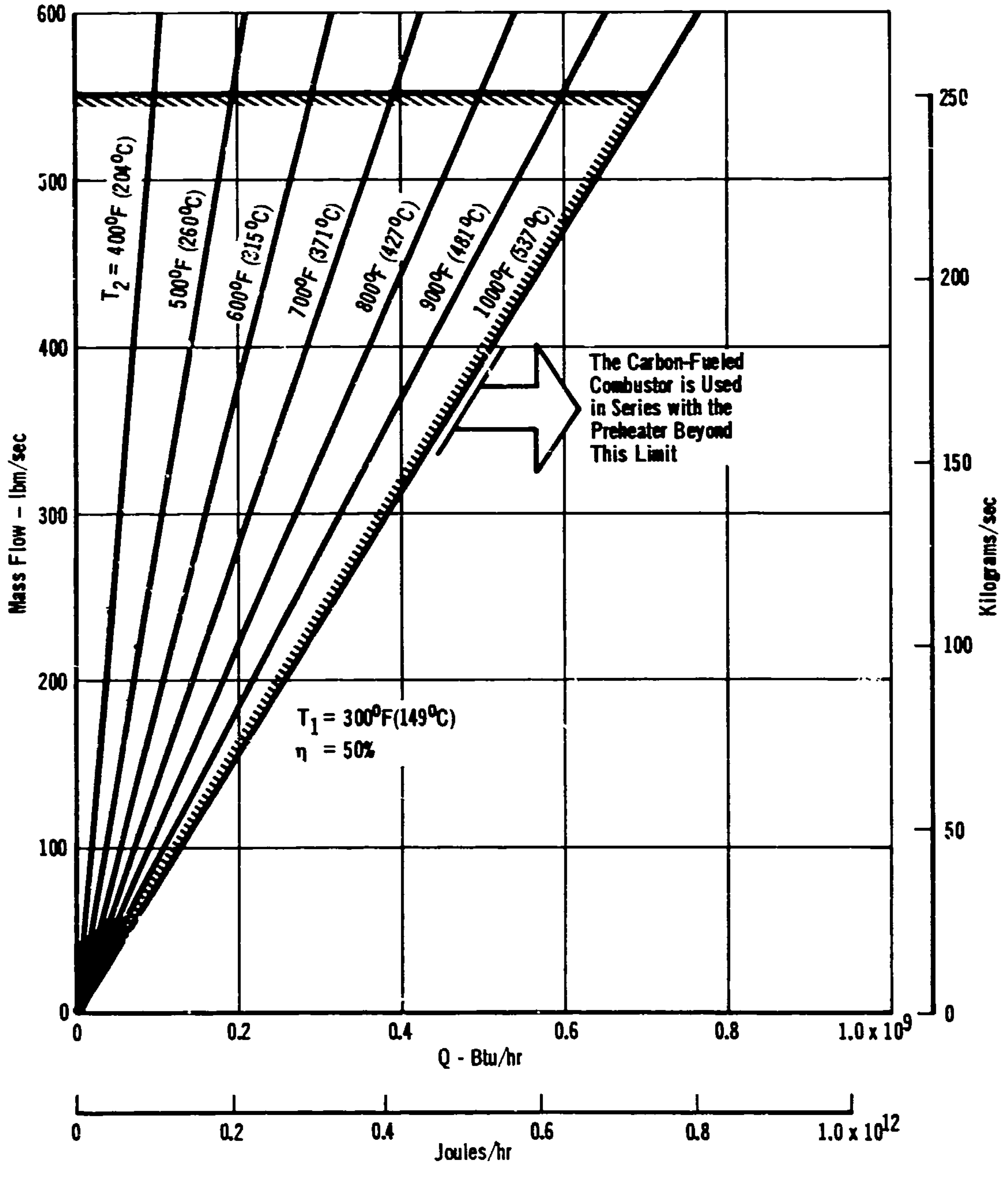
The air preheater used in the Phase II study was an electric induction heater with a stainless steel matrix similar to the heater used in the GD20 facility. The electric power required for such a heater is about 205 megawatts, and its operation is continuous.

It was decided to change the heater type to an oil-fired combustion heat exchanger to conserve greatly on both acquistion and operating costs. This was made possible technically since, during the Phase III study, it was found possible to lower the preheater outlet temperature to 1000°F (583°C) from the 1500°F (818°C) originally thought necessary. The air preheater will thus be comprised of commercially available equipment, the major design problem being the high pressure level. The heating requirements of the air preheater are shown in Figure 7-15. Some specifications of the air preheater follow:

Type	Oil-fired air to air heat exchanger
Maximum weight flow	550 lbm/sec (250 kg/sec)
Maximum pressure	3000 psia (2070 N/cm^2)
Maximum outlet temperature	1500°R (830°K)
Maximum Heating rate . . . . (50% efficiency assumed)	700 x 10^6 Btu/hr (204 MW)

The assigned confidence level of the oil fired heat exchanger is 5. Estimated cost is $7,000,000.

FIGURE 7-15
E9 AIR PREHEATER CHARACTERISTICS AND LIMITS



In Phase II the carbon combustor used on-site generated carbon monoxide (CO), based on a carbon monoxide generator at the Cabot Corporation's Ashtabula, Ohio plant. If a carbon reactor of the same size as the zirconia storage heater was utilized, about 220 lb/sec (100 kg/sec) of CO at about 3600°R (2000°K) could be manufactured based on data in Reference 9. The carbon reactor, air, oxygen, and carbon reactants, carbon charging system, and associated piping would probably cost on the order of 5 to 8 millions, using the zirconia storage heater as a reference. The carbon monoxide system is costly to acquire and could be complex to operate at pressures to 3000 psi (2060 N/cm^2). Using a carbon monoxide combustion system, the combustor system is operated in conjunction with the preheater to provide about 6000°R (3340°K) vitiated air to the scramjet test module.

In fact however, the carbon reactor supplied carbon monoxide fuel system is neither the simplest or the lowest cost. The Cabot Corporation spent considerable manpower examining the carbon combustor system to refine the concept as much as possible. The two systems they finally recommended use carbon fuel and are based on proprietory techniques associated with the Cabot Corporation's product lines. These systems will not be described in this report because of their proprietory nature. It can be stated, however, that these techniques represent a simpler, smaller process, requiring less investment, and probably lower operational costs. Maximum vitiated air temperatures in excess of 7000°R (3900°K) are achievable at pressures of 3000 psia (2060 N/cm^2). The relative proportions of the input mixtures, and output gas composition are presented in Figures 7-16 and 7-17.

Figure 7-16 shows the range of mass flow requirements of the combustor inputs as a function of flame temperature. The chemical composition of the combustion products as a function of flame temperature is shown in Figure 7-17. The molar concentration of molecular oxygen is held very close to 21% throughout the temperature range. The chemical composition of the combustion products is shown for the direct combustion of a carbon fuel manufactured by a method proprietary to the Cabot Corporation. Two alternate methods of producing carbon were suggested. The least expensive system, designated as Method A, has the highest concentration of water vapor. The combustion process described in Phase II used carbon monoxide gas and was virtually free of water vapor. This system is the most expensive, as a pebble bed reactor, a large oxygen system, and a carbon monoxide accumulator must be provided in addition to the carbon fuel generator. For Phase III, costs of the carbon system are based on an approximate estimate of Method A, the cheapest method. Method B will cost about 5 times and the carbon-monoxide system would cost very approximately 7 to 10 times Method A. The exact system chosen will depend on the assumed permissible level of water vapor in the vitiated air.

Some important specifications of the combustor system are tabulated below:

Type	Continuous combustion chamber
Temperature	1500 to 7000°R (830 to 3900°K)
Maximum mass flow	550 lbm/sec (250 kg/sec)
Maximum pressure	3000 psia (2070 N/cm^2)
Fuels:	
Carbon fuel	Provided continuously at rates up to 55 lb/sec (25 kg/sec) by proprietary method of Cabot Corporation.

FIGURE 7-16
INPUT CONSTITUENTS OF CARBON COMBUSTOR AS A FUNCTION OF FLAME TEMPERATURE
(Method A)

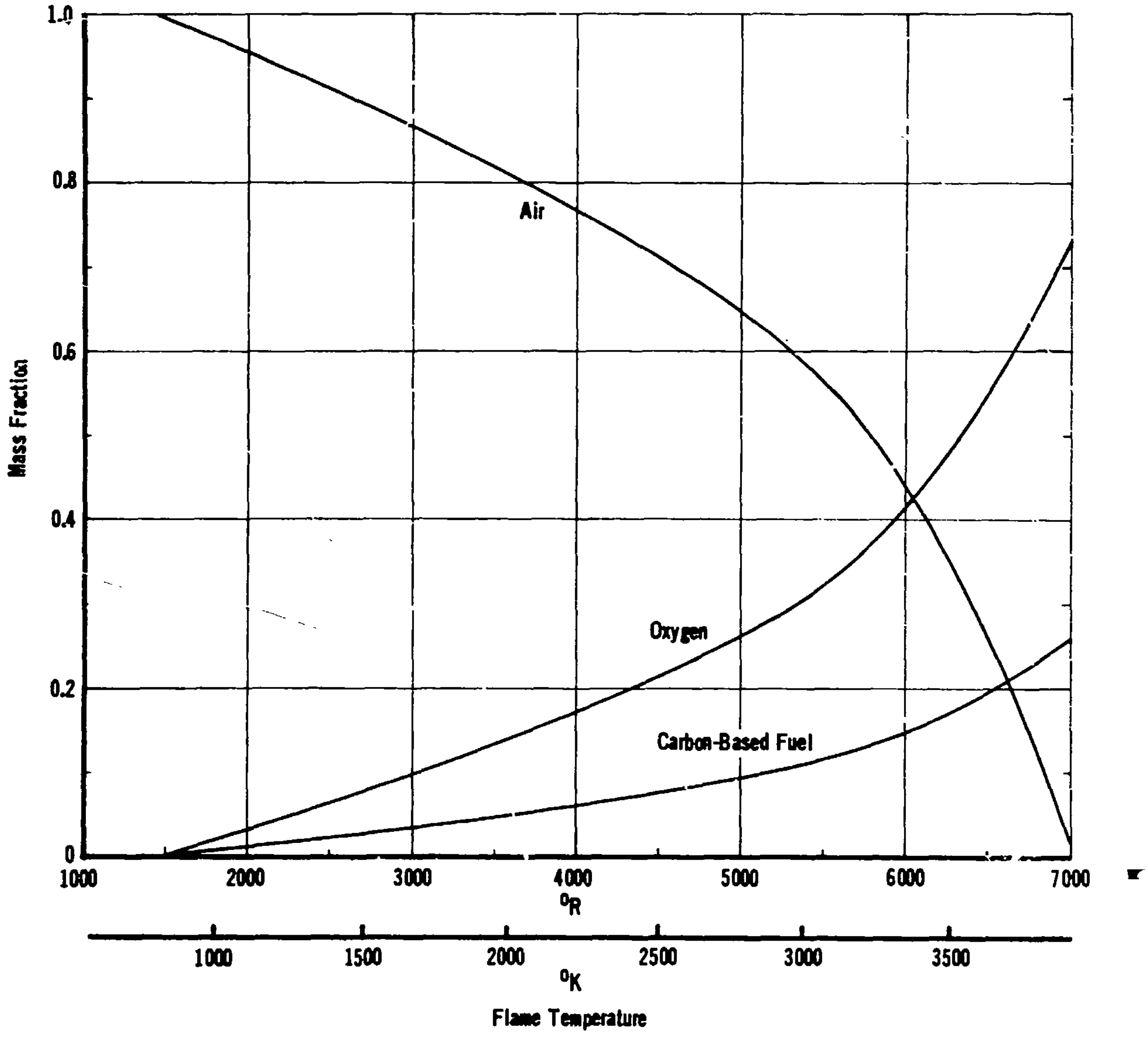
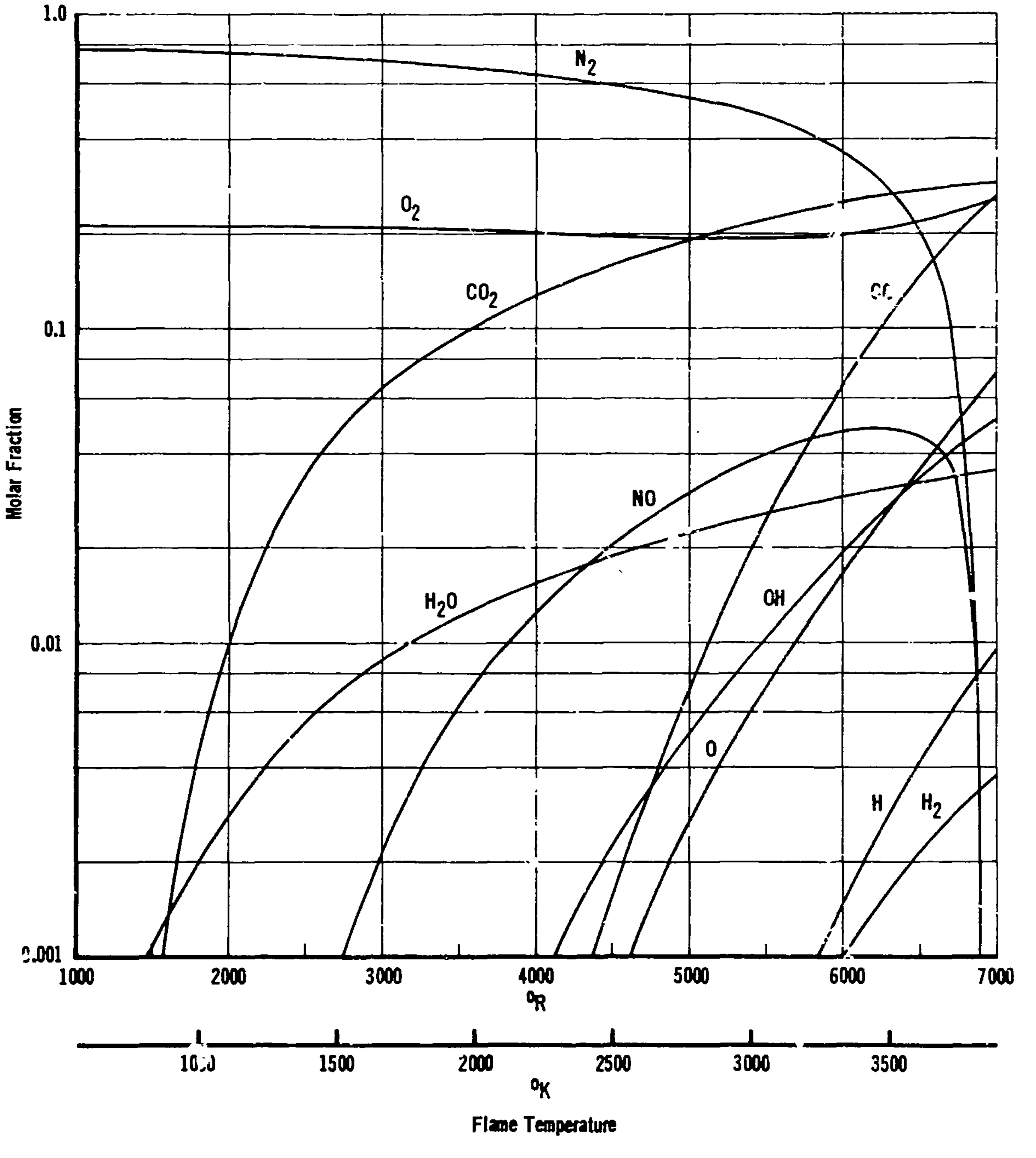


FIGURE 7-17
CHEMICAL COMPOSITION OF THE PRODUCTS OF COMBUSTION
Carbon Combustor (Method A)



Air . . . . Preheated to 1500° (830°K) by the oil fired heater previously described.
Oxygen . . . . Provided by a separate cryogenic system.

Carbon fuel and oxygen are injected annularly into the air stream from the preheater and burned. Two manifolds around the combustor shell handle the carbon and O_2 which are carried to and injected from a water-cooled expansion step in the combustor. The details of the combustor were shown in Figure 7-14.

The combustor pressure vessel employs laminated steel shell construction, with an integral water cooling system to keep the pressure shell temperatures low. A refractory clad inner liner serves to increase wall temperatures inside the combustor, reducing thermal losses. The construction is analogous to the fixed nozzle block for the scramjet test section. This type of design and fabrication is not common in wind tunnel application and will necessitate some transfer of technology to prepare a functional design and fabricate the hardware.

The combustor system will necessarily contain control systems for water cooling and carbon fuel and oxygen flow control. The water cooling system must be interlocked into the facility operational system to prevent running if the water conditions become inadequate to protect the combustor vessel. The O_2 and carbon systems will become part of an automatic facility control program integrated with the air flow control through the air preheater, at the refractory heater blowdown control, and the plug valve operation.

Safety procedures for handling the oxygen and carbon fuel and detection of excessive gas build-up will be necessary to avoid hazardous operation in terms of personnel and equipment. Frequent inspection and maintenance of the hot flow surface and injection system will be necessary. To accomplish this with ease, it may become necessary to drop the combustor out of the test circuit.

The cost of the combustor and the carbon fuel supply (Method A), is estimated at $1,000,000 and has a confidence level of 4.

7.2.4 COMPRESSOR AND EXHAUSTER PLANTS - The air weight flow requirements at altitude and Mach number for the scramjet engine test module and the thermostructural test leg nozzles were translated into facility inlet and exhaust conditions (Figures 7-18 and 7-19.

For the inlet conditions to be provided by a compressor plant, the weight flow and inlet pressure were converted to compressor inlet volume flow and pressure ratio (Pr) so as to determine total compressor requirements. Inlet volume flow was calculated at an inlet pressure of 13.8 psia (9.5 N/cm^2) to allow for inlet pressure drop, and an inlet temperature of 90°F (361°C). Relative humidity at these conditions was assumed to be 50%. The required pressure ratio was calculated by:

$$Pr = P_2/P_1 = P_2/13.8,$$

where P_2 was determined from the total pressure required at the test leg stilling chamber plus frictional pressure losses produced by the supply line and the stilling chamber hardware.

FIGURE 7-18
CHARACTERISTICS OF E9 COMPRESSOR PLANT

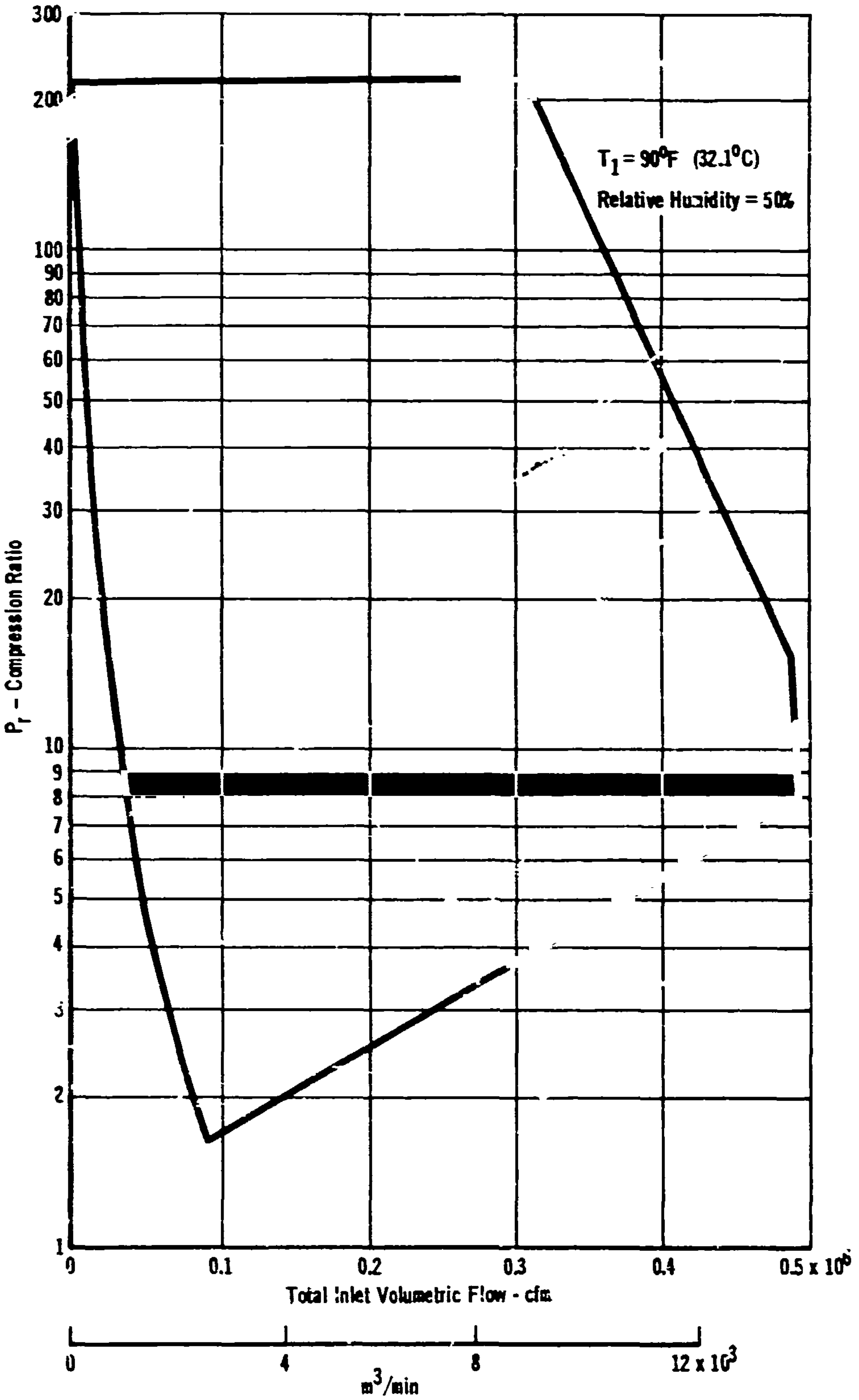
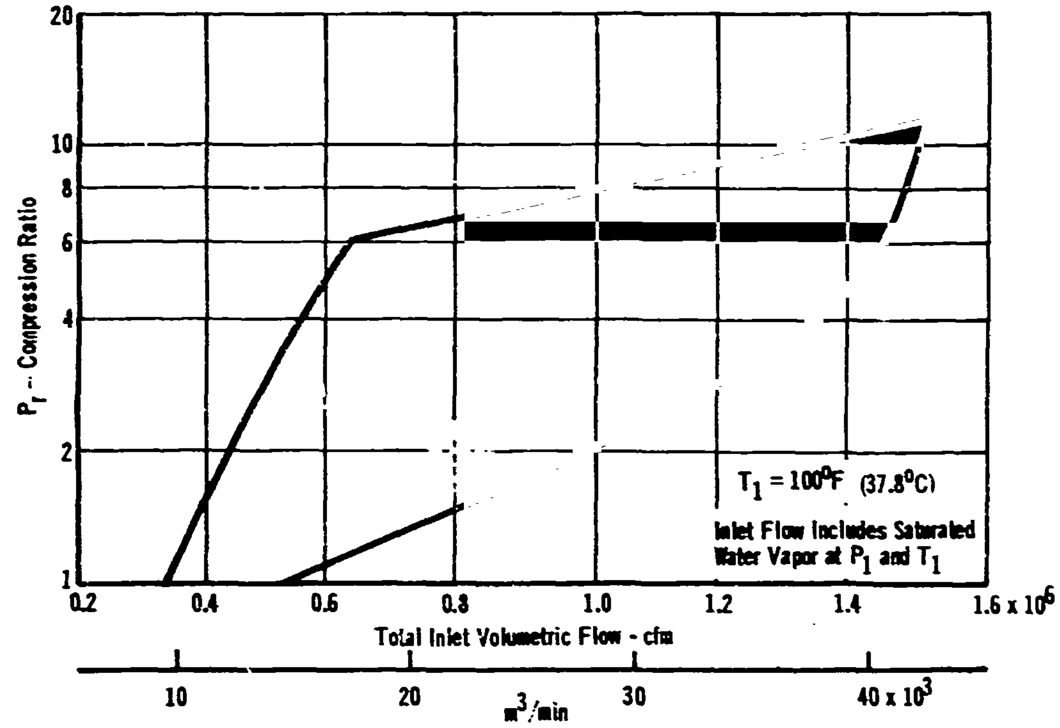


FIGURE 7-19
CHARACTERISTICS OF E9 EXHAUSTER PLANT



The results of these calculations are presented graphically in Figure 7-18, which portrays the pressure and volume flow requirements. Similar calculations were made for total exhauster requirements. In this case, Pr is defined as before, but P_1 is the variable inlet pressure and P_2 is constant, defined to be 14.7 psia (10.3 N/cm^2). Inlet temperature was assumed to be 100°F (37.8°C). Since moisture is introduced into the flow by both the combustion in the engine and by the spray cooling apparatus, the relative humidity of the flow entering the exhausters is 100% at all inlet pressures, and was accounted for in the exhauster inlet calculations. Another factor included in the total volume flow was the contribution added by the engine fuel. This was taken to be six percent for hydrogen fuel. Exhauster inlet pressure which is used to calculate both Pr and volumetric flow rate was assumed to be 100% of normal shock recovery for the Scramjet Module, and 70% of normal shock recovery for the Thermostructural Nozzles.

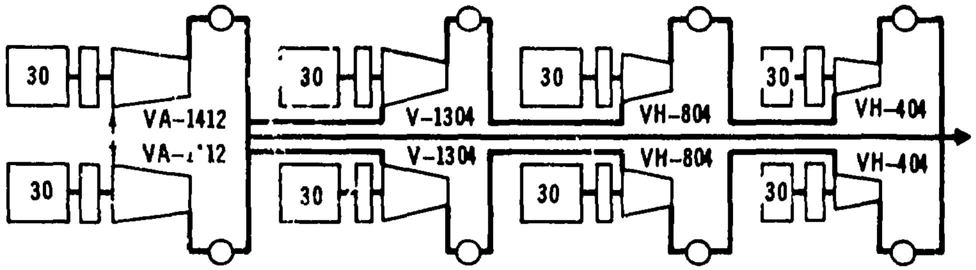
With the above assumptions, the total exhauster requirements were calculated and are shown in Figure 7-19.

In this facility, the wide difference in pressure ratios and inlet volume flow between the compressor and exhauster plants precluded any rational combination of functions in a single plant, so separate compressor and exhauster plant specifications were developed by Allis Chalmers.

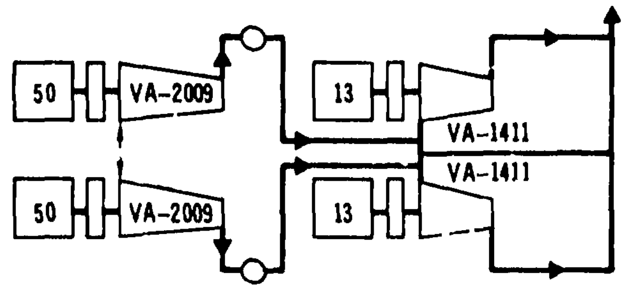
A schematic of the compressor and exhauster plants is shown in Figure 7-20, along with a list of the machines required. Both plants are straightforward, with two banks of machines each. Four stages of compression are required to obtain the

FIGURE 7-20 E9 COMPRESSOR AND EXHAUSTER PLANTS

Schematic of Compressor Plant Layout



Schematic of Exhauster Plant Layout



Compressors Required

Type Compressor	1st Stage	2nd Stage	3rd Stage	4th Stage
	VA-1412	V-1304	VH-804	VH-404
Inlet Volume - cfm (m^3/min)	250,000 (7100)	60,000 (1700)	16,100 (455)	3750 (106)
Pressure Ratio	4.2	3.73	3.73	3.73
Power - hp (kW)	30,000 (22,300)	30,000 (22,300)	30,000 (22,300)	30,000 (22,300)
Number	2	2	2	2

Exhausters Required

Type Exhauster	1st Stage	2nd Stage
	*VA-2009	*VA-1411
Inlet Volume - cfm (m^3/min)	750,000 (21,200)	250,000 (7100)
Pressure Ratio	3.0	3.7
Power - hp (kW)	50,000 (37,300)	13,000 (9700)
Number	2	2

Compressor Utility Summary

Total Power - hp (kW)	240,000	(179,000)
Cooling Water Requirements - gpm (m^3/min)	63,500	(240)
Water System Power - hp (kW)	4,600	(3,430)
Hydraulic System Power - hp (kW)	3,000	(2,230)
Total Power - hp (kW)	247,000	184,600

Exhauster Utility Summary

Total Exhauster Power - hp (kW)	126,000 (94,000)
Cooling Water Requirements - gpm (m^3/min)	10,000 (37.8)
Water System Power - hp (kW)	725 (540)
Hydraulic System Power - hp (kW)	1,000 (746)
Total Power - hp (kW)	137,725 (95,286)

Bill of Material

Compressors	Gears	Dryers
Exhausters	Switch Gear	Water Pumps
Motors	Control Center	Cooling Tower
Sole Plates	Transformers	Compressors and Exhausters
Lube Systems	Anti-Surge Control	Evacuation System
Coolers	Interconnecting Piping and Valving	

*Allis Chalmers Model Number

overall Pr = 220 needed for the compressor plant, while only two stages are needed for the exhausters. The cost of this plant is broken down as follows:

	Compressors	Exhausters
Mechanical components: Including all equipment listed on the Bill of Material plus installation and setup charges.	$38,785,000	$15,136,000
Machine footings, foundations and building.	783,000	825,000
TOTAL	$39,568,000	$15,961,000

Although this is a very large plant, all components represent hardware either available or designed, so a confidence level of 4.7 is assigned.

7.2.5 FACILITY COOLING SYSTEMS - The heat introduced into the air flow by the inlet heaters and the engine operating in the test section must be removed so that exhauster volume flow is reduced to a minimum and that flow temperature is low enough for reliable operation of the downstream configuration valving and exhauster machinery.

A water spray, located directly behind the test section, is used to drop the flow temperature from temperatures in the 6500°R (3600°K) range to about 100 to 210°F (37.8 to 99°C). The actual temperature downstream of the spray is a unique function of pressure. Likewise, the amount of water required per pound of dry air is a unique function of the static pressure, for a given upstream air temperature. These fractions are similar to those shown in Figure 6-11, except an upstream air temperature of 6000°F (3310°C) and an initial water temperature of 80°F (26.7 °C) is assumed for E9. The minimum downstream temperature under these conditions is also shown as a function of static pressure. If excess water is sprayed in, no additional cooling will be obtained, the excess being drained to the barometric well. With the range of air flows available in E9, a spray system consisting of a lake water reservoir, pumping station, piping and valving with a maximum water flow rate of 7920 gpm (29.6 m^3/min) is required.

Maximum allowable exhauster inlet temperature is 100°F (37.8°C). An air-to-water heat exchange system is installed downstream of the spray cooling unit to obtain this final increment of cooling. As the temperature of the wet air mixture drops in the cooler, nearby all of the water vapor introduced by the spray cooler is condensed out of the flow, greatly reducing the volume flow to the exhausters. The heat exchangers, known as dehumidification coolers, are built in individual units, two on each exhauster bank inlet pipe. These coolers are each 28 ft (8.5 m) in diameter and approximately 50 ft (15.3 m) long. Each cooler is serviced by a water supply system which brings 80°F (26.7°C) water from a lake or reservoir and returns the warm water to the reservoir.

A third cooling system is provided for the backside cooling of the scramjet module flex plate nozzle, the thermostructural nozzles, and diffuser sections. This system is a closed-loop demineralized water system, incorporating a water-to-water heat exchanger. Chilled water for the heat exchanger is provided by reservoir water.

A brief summary of the three cooling systems follows:

SPRAY COOLING:

Maximum Flow Rate	7920 gpm (29.6 m^3/min)
Maximum Pressure	30 psi (20.8 N/cm^2)
Pump Horsepower	615 hp (460 kW)
Cost	$292,000

DEHUMIDIFICATION COOLERS:

Heat Exchangers - 4 Finned Tube Type Units, Each 28 ft (8.5 m) Dia X 50 ft (15.3 m) Long

Maximum Flow Inlet Temp	210°F (99°C)
Outlet Temp (All Conditions)	100°F (37.8°C)
Max. Total Weight Mixture Flow Rate	1650 lbm/sec (746 kg/sec)
Max. Heat Exchange Requirements	4.6 x 10^9 Btu/hr (1350 MW)
Total Water Flow Requirements (Provided in Two Separate Systems)	265,000 gpm (1000 m^3/min)
Total Power	26,400 hp (19,600 kW)
Cost	$10,500,000

BACKSIDE WATER COOLING:

Demineralized Water System	
Flow Rate	3510 gpm (13.3 m^3/min)
Maximum Pressure	2120 psia (146 N/cm^2)
Minimum Water Temperature	80°F (26.7°C)
Maximum Water Temperature	210°F (99°C)
Water Pump Power	5900 hp (4400 kW)
Water to Water Heat Exchangers	
Maximum Heat Exchange Required	360 x 10^6 Btu/hr (10 MW)
Reservoir Water Pressure	60,150 gpm (228 m^3/min)
Maximum Water Pressure	130 psia (90 N/cm^2)
Water Pump Power	8,800 hp (6550 kW)
Cost	$3,444,000

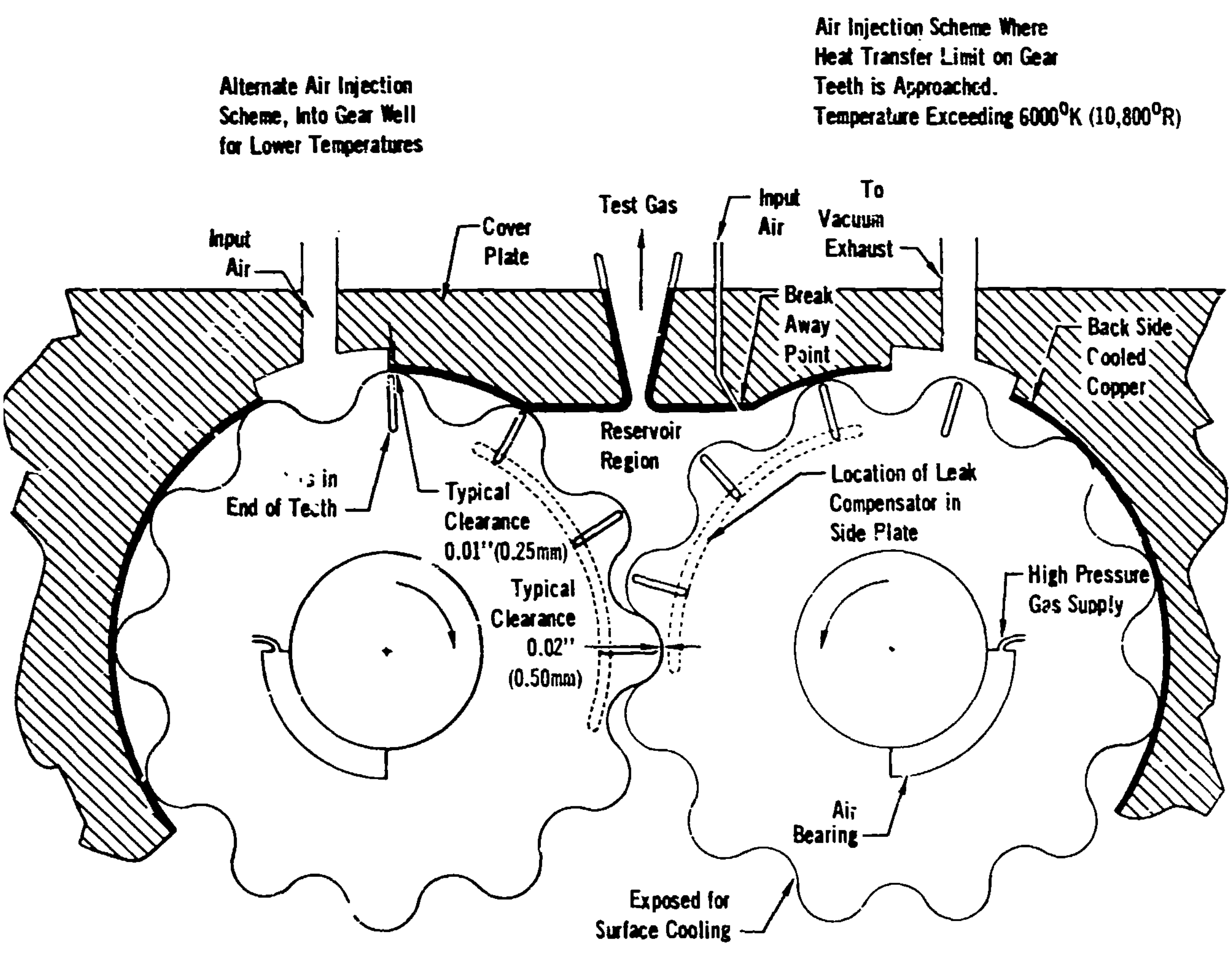
The total water cooling requirements, though large, require the application of large quantities of industrial sized equipment, and do not require the development of new techniques. A confidence level of 4 is assigned.

7.2.6 MULTI-RECOMPRESSION HEATER CONCEPT TO SUPPLEMENT E9 CAPABILITY - In Phase II, an en[illegible] facility based on Weatherston's multi-recompression heater was evalu[illegible]). In the size originally proposed by Weatherston, about 75 M[illegible] power were necessary to power the facility. The Phase II scr[illegible] (E8) required about ten times that value. The delivery of thi[illegible] rotors about 4 feet (1.2 m) diameter and 5 feet (1.5 m[illegible] challenge current power transmission technology severely. Althou[illegible]ssion heater concept is probably feasible, in the size required [illegible] appear to be a viable concept without a major development pr[illegible] 100 million dollars. This fact was a major consideration [illegible] E8 into Phase III for refinement. Two multi-recompression heaters were required to cover the mass flow and enthalpy range for simulated Mach number 3 to 12 flight. As the analysis of E9 continued in Phase III, it appeared that the small, high enthalpy multi-recompression heater from E8 in Phase II would fit into the E9 concept to supply additional clean air capability, when and if the concept were developed. This section discusses some of the alternatives available to integrate this concept into E9, and an order of magnitude estimate of what the acquisition cost might be.

The multi-recompression heater is a mechanical device which converts shaft power into thermal energy. The basic operation involves a rapid succession of free expansions and work input recompression processes. This is accomplished in a device which is structurally related to a gear pump, but which differs in its basic principle of operation. The power concentration is very high when this device is driven at the highest practical speeds. A schematic of this concept is shown in Figure 7-21, showing two methods of gas input, depending on the operating temperature. The power density of this device, which operates at pitch-line speeds of up to 800 ft/sec (244 m/sec), is comparable to a piston of 2.8 in (7 cm) diameter moving against a 300 atmosphere pressure (3039 N/cm^2) at a velocity of 800 ft/sec (244 m/sec), and requires an input of 250,000 hp (186,00 kW).

FIGURE 7-21

MULTIRECOMPRESSION HEATER CONCEPT, WITH SIDE PLATE REMOVED



Based on data developed in Volume III, the dimensions of the multi-recompression rotor required to match the mass flow of E9, from 4500°R (2500°K) to the throat heat transfer limit are 55.3 in (1.4 m) diameter, 67.3 in (1.7 m) long, with 12 teeth 6.7 in (17 cm) deep. The performance of this machine and its power requirements are shown in Figure 7-22.

The maximum performance of this system over the carbon combustor concept is shown as zone (2) in Figures 7-2 and 7-6. The magnitude of the power source required to deliver about 1300 MW of power to two rotors about 5 ft. (1.5 m) in diameter is impressive. In actuality, two modes of operation are available, as proposed by Weatherston. One mode of operation would be on an intermittent basis using flywheels to store kinetic energy sufficient to maintain a relatively uniform run condition over a short run period. In this mode, the heater concept would supplement the zirconia storage heater to provide an air testing capability from Mach 3 to Mach 12.5 with flight duplicated conditions on an intermittent run basis. The other mode of operation would be on a continuous basis supplementing the carbon combustor at temperatures above 4500°R (2500°K), thus providing nearly pure air up to 4500°R (2500°K) and clean air from that point to almost 10,800°R (6000°K) on a continuous basis. Figure 7-23 contrasts the continuous installation versus intermittent installation. The flywheels are designed to supply the test conditions over a 30-second run with a ± 5% variation. From data presented in Section 3, 26 General Electric GE4/J5P engines are required as gas generators to drive two free turbines which power the two rotors. The confidence level associated with this development is 1, indicating maximum risk. The estimated costs of adding this system to an existing E9 facility are:

ACQUISITION COSTS ($1000)

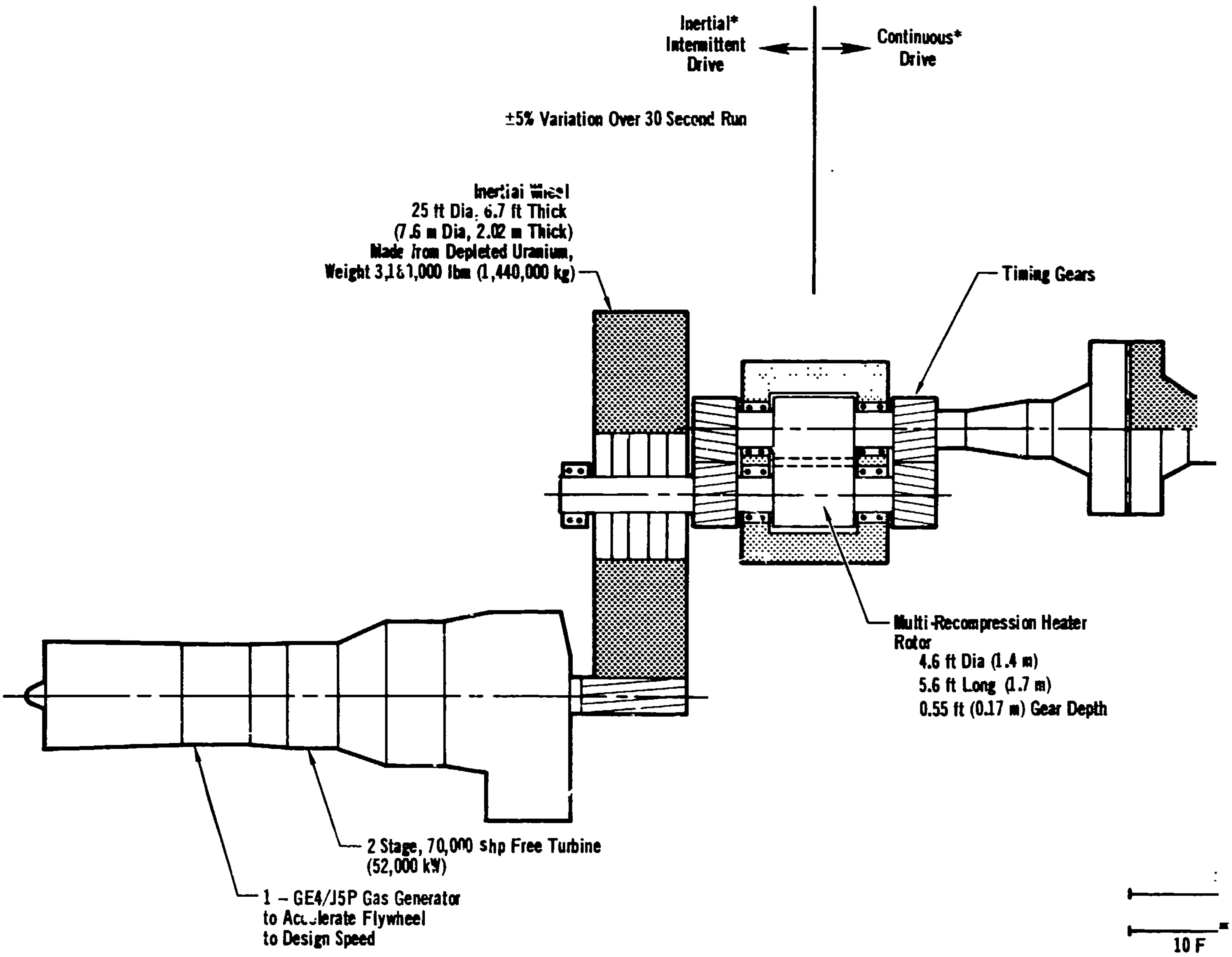
INTERMITTENT	CONTINUOUS	ITEM
45,000	60,000	Multi-Recompression Heater, Including Development Costs
4,000	61,000	Drive System
4,200	105,000	Gas Turbine Engines
10,000	15,000	Integration into Basic E9 Facility
63,200	241,000	Total

7.2.7 <u>COST SUMMARY</u> - Figure 7-24 presents a detailed cost breakdown for the E9 facility, based on costing techniques described in Section 2, as necessary to acquire the entire facility. There currently exists no similar facility into which E9 can be integrated. If the planned AEDC TRIPLTEE Facility is acquired, however, it would form the logical base into which the E9 concept could be integrated. The cost savings would be minimal since TRIPLTEE is presently conceived as an intermittent facility. Integration of E9 into this concept would convert it into a continuous operation facility. Probably no more than about 20 million dollars would be saved by the integration. The primary benefit would be in acquiring the operating experience associated with the TRIPLTEE staff.

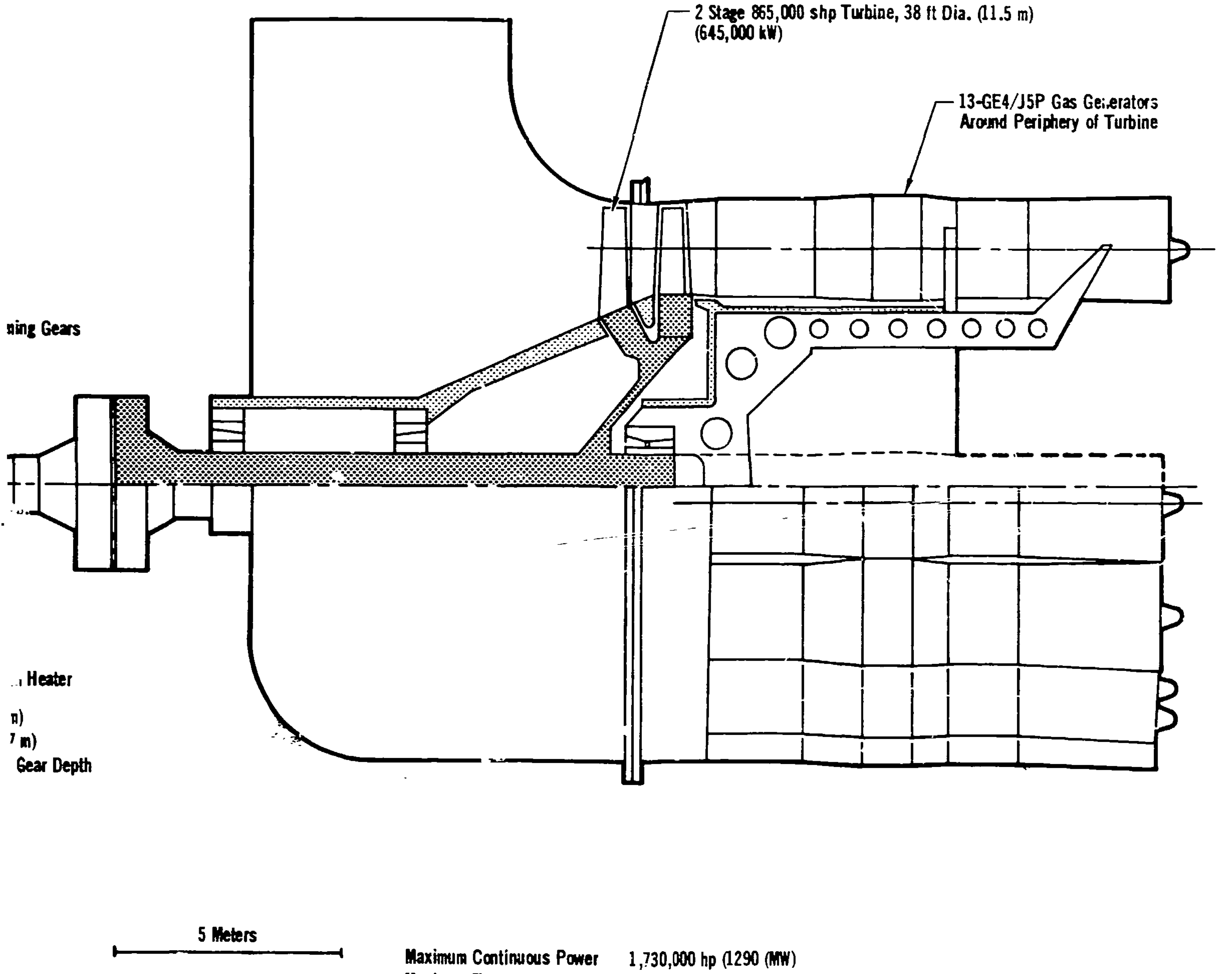
FIGURE 7-22
PERFORMANCE OF SUPPLEMENTAL MULTIRECOMPRESSION HEATER FOR E9

M_∞	P_o psia (N/cm^2)	T_o °R (°K)	$\dot{w}$ lb/sec (kg/sec)	Power Factor Btu/sec-psi ($kW\text{-}cm^2/N$)	Rotor Speed rpm	Power $hp \times 10^{-6}$ (MW)	Torque $ft\text{-}lb \times 10^{-6}$ (MN-m)	Remarks
8	1980 (1370)	4500 (2500)	550 (250)	320 (490)	2560	.90 (670)	1.75 (2.28)	
8.6	3110 (2150)	5000 (2800)	550 (250)	228 (350)	1820	1.01 (750)	2.90 (2.78)	
9.0	4110 (2830)	5600 (3100)	550 (250)	192 (292)	1530	1.12 (834)	3.83 (5.00)	
9.5	6350 (4390)	6200 (3400)	550 (250)	132 (202)	1060	1.19 (886)	5.50 (7.17)	Throat cooling limit reached.
9.7	7000 (4830)	6400 (3550)	550 (250)	124 (189)	990	1.23 (920)	6.55 (8.55)	Maximum pressure & torque
10.0	6480 (4460)	6700 (3700)	550 (250)	137 (210)	1100	1.28 (960)	6.14 (8.00)	
10.5	5300 (3650)	7400 (4100)	550 (250)	200 (306)	1600	1.50 (1120)	4.92 (6.40)	
11.0	4660 (3220)	8100 (4500)	550 (250)	262 (400)	2100	1.73 (1290)	4.32 (5.60)	Maximum Power
11.5	3580 (2470)	9000 (5000)	460 (280)	340 (520)	2720	1.73 (1290)	3.30 (4.30)	Maximum Power
12.0	3200 (2210)	9600 (5300)	348 (158)	340 (520)	2720	1.52 (1150)	2.98 (3.69)	
12.5	2800 (1930)	10400 (5800)	262 (118)	340 (520)	2720	1.37 (1020)	2.72 (3.52)	

FIGURE 7-23
DRIVE SYSTEM CONCEPT FOR SUPPLEMENTAL MULTI-RECOMPRESSION HEATER SYSTEM



*Left side of figure illustrates schematically one-half of the equipment needed to operate on an intermittent basis with inertial energy storage while right side of figure illustrates one-half of the gas generators and power turbines needed to operate on a continuous basis.



Maximum Continuous Power	1,730,000 hp (1290 (MW)
Maximum Torque	6,500,000 ft-lb (8,750,000 N-m)
Maximum Speed	2720 rpm

FOLDOUT FRAME 2

FIGURE 7-24
COST SUMMARY – E9

Sheet 1 of 2

Facility Component	Cost ($1000's)
Test Leg	
Footings and foundations	836
Scramjet test module	15,152
Water cooled diffuser spools	2,164
Muffler	230
Subtotal Test Leg	18,383
Thermostructure Test Accessories	
Thermostructure test cabin	1,058
Mach 6 nozzle and diffuser	853
Mach 9 nozzle and diffuser	1,499
Mach 12 nozzle and diffuser	2,091
Water cooled diffuser spools	846
Subtotal Thermostructure Test Accessories	6,347
Oil/Gas Fired Combustion Heat Exchanger	7,000
Incl Boiler	
Hot air pipe	
Cold air pipe	
Zirconia Storage Heater	
Cold air pipe	250
Heater shell and foundation	1,366
Premix burners	500
Alumina brick	773
Zirconia brick	2,500
Thermal insulation	1,800
Subtotal Zirconia Storage Heater	7,189
Carbon Fuel System	1,000
Compressor Plant	
Building	783
Compressor	31,105
Piping (to heaters)	3,072
Control valves	4,608
Subtotal Compressor Plant	39,568
Exhauster Plant	
Building	625
Exhauster	11,236
Piping (to exhaust muffler)	1,560
Control valves	2,340
Subtotal Exhauster Plant	15,961

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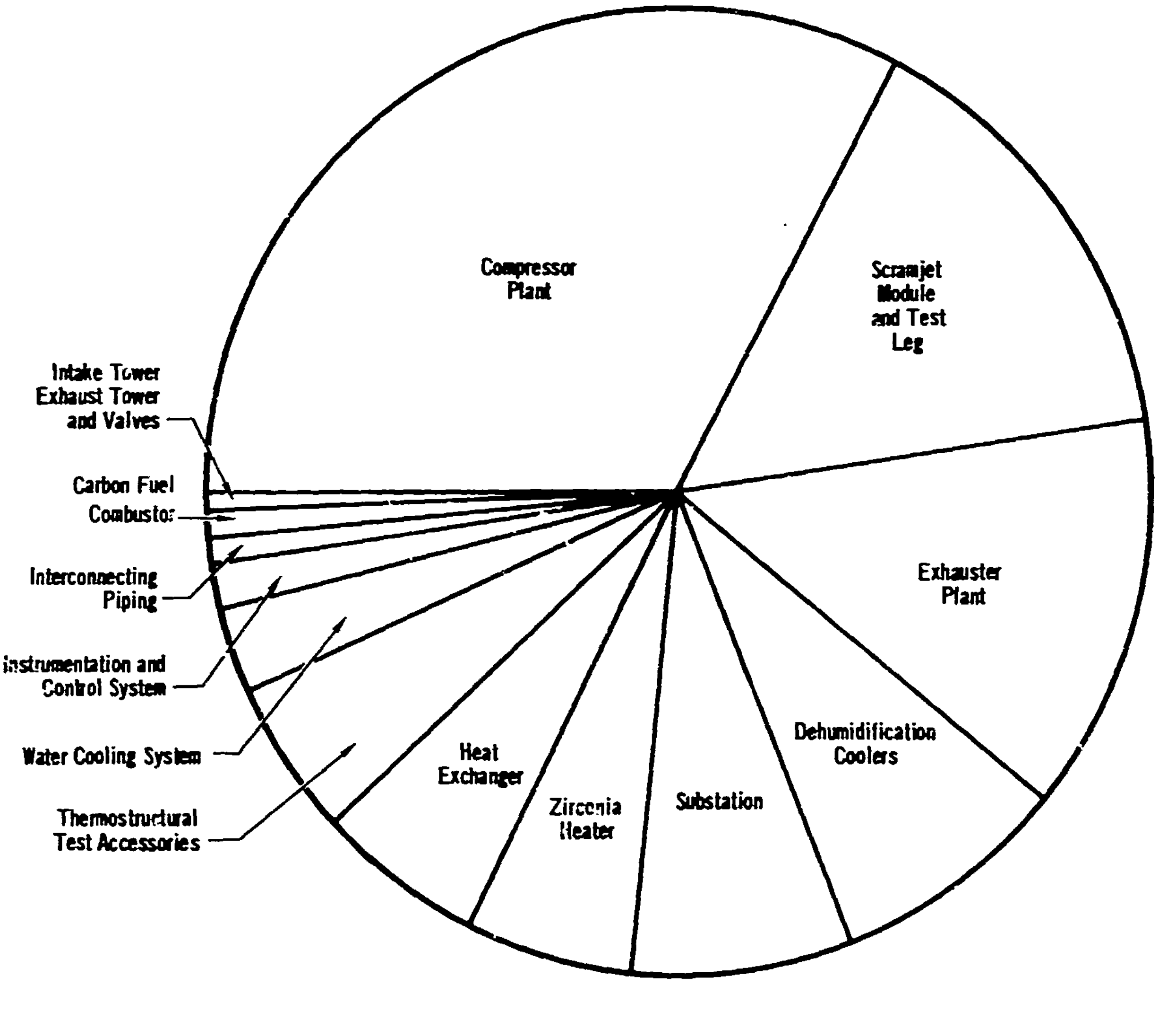
FIGURE 7-24 (Continued)
COST SUMMARY – E9

Sheet 2 of 2

Facility Component	Cost ($1000's)
Dehumidification Coolers	10,792
Intake Tower	100
Miscellaneous Valves	467
Miscellaneous Piping	807
Test Leg Water Cooling System	3,444
Substation	9,000
Automatic Facility Control System	400
Instrumentation and Data Acquisition System	1,100
Total E9 Components	121,558
Contengency @ 10%	12,156
Total E9 Facility Cost	133,714
A & E Fee @ 6%	8,021
Management and Construction Coordination Fee @ 4%	5,350
Grand Total E9	147,085

The contributions of the components to the total cost can best be illustrated by Figure 7-25. The dominant cost of the compressor plant, exhauster plant, and scramjet test section (about 60% of total cost) is indicative of the lack of cost reduction possibilities by integration into an existing facility complex. This compressor and exhauster plant represents considerably more capacity than found at research establishments.

FIGURE 7-25
DISTRIBUTION OF ACQUISITION COSTS FOR E9
Total Acquisition Cost: $147,085,000



As for E20, the systems required to provide high pressure, heated continuous airflow are the major cost contributors, exceeding by far the cost of the actual test apparatus. Because of this cost relationship, for instance, having provided compressors, exhausters, heaters, cooling for the scramjet test module, it is possible to add the thermostructural test capability at a very low relative cost, in this case, 4.8% of the total cost.

The operating costs were calculated according to the methods of Section 2.3.2, using the following assumptions:

U_p	= Power Utilization Factor	= .5
U_c	= Consumable Utilization Factor	= .5 For Carbon and LO_2 = .9 For Fuel Oil
CUF	= Cryogenic Utilization Factor	= 1.54 for LO_2
U_R	= Run Utilization Factor	= .3
R_p	= Power Cost	= .0065 (Utility Power)
R_c	= Consumable Cost	= \$.10/gal (Fuel Oil) (\$26/m^3) = .04/lb (Carbon) (.088/kg) = .061/lb (LO_2) (.134/kg)
U_F	= Facility Utilization Factor	= .6
Annual Maintenance Cost		= \$2,700,000
N_s	= Direct Staffing	= 75

The annual maintenance costs were based on scaling historic data obtained from AEDC, and major equipment suppliers. This cost includes only parts and equipment, manpower costs are included in the 75 people staffing. Utilizing these factors, the cost equations in 2.3.12 were evaluated. The cost per facility occupancy hour is then:

Electric Utility	415
Fuel Oil	126
Carbon Fuel	1190
LO_2	791
Energy	2522
Staffing	2500
Maintenance	2250
	\$7272/Occupancy Hour

7.3 SPECIFIC SITE CONSIDERATIONS

In addition to the general site considerations in Section 2.7, E9 poses problems in two additional areas, namely, the potential noise associated with its operation, and the storage of large quantities of chemical fuels and oxidizers in proximity to each other. Atmospheric pollution contributed by this facility should be minimal, for with cooling water sprays and dehumidifying coolers which remove 99% of the water vapor, most of the water soluable contaminants should be removed from the exhaust gases. Given its independent cooling water supply, such as Wood's Reservoir at AEDC, the overall impact on the surrounding environment could be minimized.

The muffler concept which satisfied the restrictions given in Appendix A was designed for about 2000 lb/sec (906 kg/sec). Thus for the 550 lb/sec (250 kg/sec) for E9 a very satisfactory sound level should be possible. The large quantities of fuel and oxidizers however will require a remote site, yet with general access for shipment of outsized subassemblies for field fabrication. There are probably many sites which could satisfy these requirements, such as the Marshal Space Flight Center at Huntsville, Alabama. This site has been used to test F-1 rocket engines, with their resultant high noise levels and requirements for storing large quantities of liquid hydrogen and oxygen. However, an overriding consideration is probably the experience level of the potential operating staff in operating zirconia storage heaters, since TRIPLTEE will eventually employ two or three zirconia heaters of the size of the one zirconia heater required for E9. If TRIPLTEE is nearing operation or is in operation at the time E9 would be planned, in all probability AEDC should be considered as the most suitable site because of the concentration of personnel and equipment engaged in nearly identical tasks, and the suitable base to integrate into.

7.4 DEVELOPMENT ASSESSMENT

The general ground rules for the development assessment are presented in Section 2.4. Individual component assessments are contained in each subsection discussion of the facility components, and are summarized in this section.

Item	Cost Fraction (K_i)	Confidence Level (C_{L_i})	$K_iC_{L_i}$	Percent Technical Risk	Technical Risk Ranking
Scramjet Test Section	.151	2	.302	32.98	1
Thermo/Structures Test Leg	.052	4	.208	5.68	5
Zirconia Heater	.059	4	.236	6.44	4
Oil Fired Heat Exchanger	.057	5	.285	3.11	7
Carbon Combustor/Supply	.008	4	.024	1.31	9
Oxygen System	.005	5	.025	.27	10
Compressor and Exhauster Plants	.448	4.7	2.11	31.83	2
Dehumidifying Coolers	.089	4	.356	9.72	3
Cooling Water System	.028	4	.112	3.06	8
Balance of Equipment	.103	5	.515	5.62	6
Total	1.00		4.17	100.0	

The numerical confidence level associated with the development assessment of E9 is equal to 4.17. This quantified evaluation is generally consistent with a subjective evaluation that E9 represents a larger version of mechanical concepts in the present technology and represents a unique assembly of this equipment. The transfer of a proprietary technology from a commercial industry will require a significant effort, and is reflected in the level 3 assigned to the carbon combustor. This facility should not represent a major challenge to the current fabrication capability, although some processes unique to the aircraft industry are employed. The major items in the technical risk ranking are the large compressor/exhauster plant and scramjet test section. The integration of three heater concepts into one operating system presents a challenge to the designers, but probably one for which acceptable design solutions are available from current experience.

The addition of the multi-recompression concept greatly adds to the technical uncertainty. Verification of the successful, safe, and reliable operation of a device absorbing 1920 MW is an important question. For this reason, the lowest confidence level of 1 was assigned the multi-recompression heater concept. Using the costs presented in 7.2.6, the following numerical ratings were obtained for adding a MRCH to E9.

Intermittent MRCH Plus E9

Item	K_i	C_{L_i}	$K_iC_{L_i}$	Percent Technical Risk
E9	.66	4.17	2.75	41.5
Intermittent MRCH	.34	1.00	.34	58.5
Total	1.00		3.09	100.0

Continuous MRCH Plus E9

Item	K_i	C_{L_i}	$K_iC_{L_i}$	Percent Technical Risk
E9	.33	4.17	1.38	15.0
Continuous MRCH	.67	1.00	.67	85.0
Total	1.00		2.05	100.0

The composite confidence level of the E9 facility thus drops from 4.17 for the basic facility to 3.09 when an intermittent multi-recompression heater is added and and 2.05 when a continuous operating MRCH is added. In both cases, the MRCH represents the majority of the total technical risk. This evaluation is indicative of the increased uncertainty that the performance goals can be met, as specified. One way to reduce the uncertainty for the multi-recompression heater concept would be development of a prototype in the 150 MW power class. In reality, even this prototype would only come after development of perhaps a 15 MW device for initial design criteria development.

In summary, although E9 represents a collection of technologies not previously proposed, the facility incorporates concepts each proven in their own applications.

The major challenge is to assemble these working facets into an overall system. The uncertainty that the design performance will be attained is not large, even though a period of working out the various operational features of the facility may be necessary.

7.5 ACQUISITION SCHEDULE AND TIMING

The schedule for acquisition E9 is presented in Figure 7-26, and is based on the general considerations given in Section 2.8. It is seen that the facility can be available for use in about 5-1/2 years. Some time elements could be reduced if the program were conducted on a crash basis, but the proposed schedule is conservative, and allowance has been made for the usual slippage on a major facility effort. The total period of 65 months embraces facility demonstration tests as well as calibrations and may be longer than would be allowed under the pressure of test program schedule demands. Still, this time should be spent before routine test programs are scheduled. The cost and schedule for acquisition of the complete facility as specified are then:

Cost	$147,085,000
Schedule	65 Months

The final performance goals need not necessarily represent the initial undertaking. At the expense of increasing total costs, the annual costs could be reduced by initiating a stretched out program where the initial facility performance is less than the final goal. This requires sufficient planning so additional performance increments can be added without significant interruption of the basic facility operation.

A limited amount of money could be deferred by later acquisition of the thermostructural test leg components (about 6.4 million dollars), but significant decrease in the overall facility capability would result if deferred indefinitely. The acquisition of TRIPLTEE would have a definite impact on the cost and schedule associated with E9. Since the zirconia storage heater for E9 is essentially a TRIPLTEE sized heater, E9 could be incorporated into the TRIPLTEE facility complex for about 0.8 of the basic E9 costs. In fact, the purposes of E9 and TRIPLTEE are nearly identical, the latter facility concept being essentially E9 without the carbon combustor concept, and limited to intermittent operation rather than continuous. If the necessity for pure air engine research is overwhelming, a multi-recompression heater could be added to the facility which would provide the same conditions as the carbon combustor, up to the throat cooling limits (see Figure 7-6). For continuous operation, the cost of acquiring the power alone would be 104 million dollars, for 26 ground power versions of the GE 4/J5P. Assuming the gearing problems could be solved, and a multi-recompression heater of the size required could be developed, probably on the order of 200 to 300 million dollars would be required to add the air capability on a continuous basis.

Developing the multi-recompression heater as an intermittent facility consistent with the operation of the zirconia storage heater would eliminate about 100 million dollars in gas turbine drives, but the development costs for the multi-recompression heater and gearing would remain. The inertial wheels required to store enough energy so that a 5% reduction in test conditions occurs during a 30-second run are about 23 feet (7.6 m) in diameter, would be made of depleted uranium, and weigh about 3,180,000 lb (1,440,000 kg) per wheel. This alternative appears to contain too high a technical risk and cost increment for the benefits gained to make it a viable concept. Development of the multi-recompression heater in a size consistent with Weatherston's original recommendations (Reference (10)) appears feasible, but not in the size required for obtaining the additional air performance for E9.

The 5-1/2 year acquisition schedule shown in Figure 7-26 is not considered unreasonable for a facility of the scope of E9. Since E9 is essentially an add-on capability to a zirconia storage heater facility, there is no reason why an existing small facility could not be modified to incorporate the design features of E9. A facility such as the PARD zirconia heater at Langley Research Center could be used. Cored brick could be substituted for the present pebble matrix, and a small combustor capable of about 40 lb/sec (18 kg/sec) could be incorporated into the design to operate in an intermittent mode initially, and perhaps a continuous mode at a later date. This would not only provide a 40 lb/sec (18 kg/sec), 700°R (3900°K) facility which adds to the capability of LRC, but also could provide the necessary operating experience and design criteria for E9 at low cost. Probably less than 2 or 3 million dollars would be required to accomplish the transformation if maximum use of existing and surplus hardware were made.

7.6 EVALUATION SUMMARY

Unlike the gasdynamic facilities, which provide their research data using subscale models which are structurally dissimilar to the actual aircraft, the contribution of the engine research facilities is related to the realism in size and structure of the engine components. Further simplification can be made for ramjets because, unlike turbomachinery, there are no rotating components present. Concepts such as the scramjet test section, representing a two-dimensional longitudinal slice through the engine, can provide a significant research capability without attempting to duplicate the entire engine and flow field.

The engine research facilities, being flight duplicators, provide the pressure, temperature and velocity corresponding to a given altitude and Mach number. Unless full scale models, or actual flight hardware are used, full scale Reynolds numbers will not be obtained. That is, for a 30% model, the Reynolds number will be 30% the full scale value. At lower Reynolds number, the skin friction coefficient, heat transfer coefficient, and boundary layer thickness growth rate are all greater, so that frictional thrust losses and wall heat transfer rates will be greater for a model, than for a full scale test article. This implies that for flight duplicated conditions with subscale models, experimental data will yield conservative results.

Unlike the compound turbomachinery engine facility (E20), it was not judged practical to provide an entire engine test capability for the large ramjet engines associated with operational aircraft. It was judged sufficient for research programs, and to demonstrate engine operation, to provide a facility capable of accommodating a single engine module.

In Phase II, a primary consideration was how small a module would be sufficient to yield research data which could be satisfactorily extrapolated to full scale sizes. In order to provide this answer, the characteristics of scramjet engines associated with various sizes of aircraft and models were evaluated. An engine module capture area of 15 ft^2 (1.39 m^2) was judged sufficient to accomplish a significant portion of the necessary research. However, in obtaining the most recent data for zirconia storage heaters, it appeared that the Phase II size heater would accommodate almost three times its original estimated mass flow using a cored brick

FIGURE 7-26
ACQUISITION SCHEDULE, DUAL MODE RAMJET ENGINE RESEARCH FACILITY (E9)

	ACTIVITY
1	Basic Specifications, Construction Concepts
2	Facility Design Concepts
3	Facility Preliminary Design
4	Carbon Fuel System Verification
5	Facility Final Design
6	Scramjet Leg
7	Aerothermodynamic Leg
8	Compressor/Exhauster Plant
9	Engine Fuel Systems
10	Air Preheater
11	Carbon Fuel Combustor
12	Zirconia Heater
13	Water Cooling Systems
14	Preliminary Site Considerations
15	Site Recommendations
16	Bid Package and Construction Plan
17	Letting of Bids
18	Site Preparation and Integration Development
19	Preliminary Site Work and Shop Fabrication
20	Compressor Fabrication
21	Field Fabrication, Installation
22	Scramjet Leg
23	Aerothermodynamic Leg
24	Compressor/Exhaust Plant
25	Engine Fuel Systems
26	Air Preheater
27	Carbon Fuel Combustor
28	Zirconia Heater
29	Manufacturing Ceramic Matrix
30	Water Cooling Systems
31	Demonstration Tests
32	Components
33	Subsystems
34	Complete Facility
35	Shakedown and Calibration
36	
37	
38	Resolution of Proprietary Items and Technology Transfer
39	
40	
41	Development of Operating Methodology and Assembly of Operating Staff
42	
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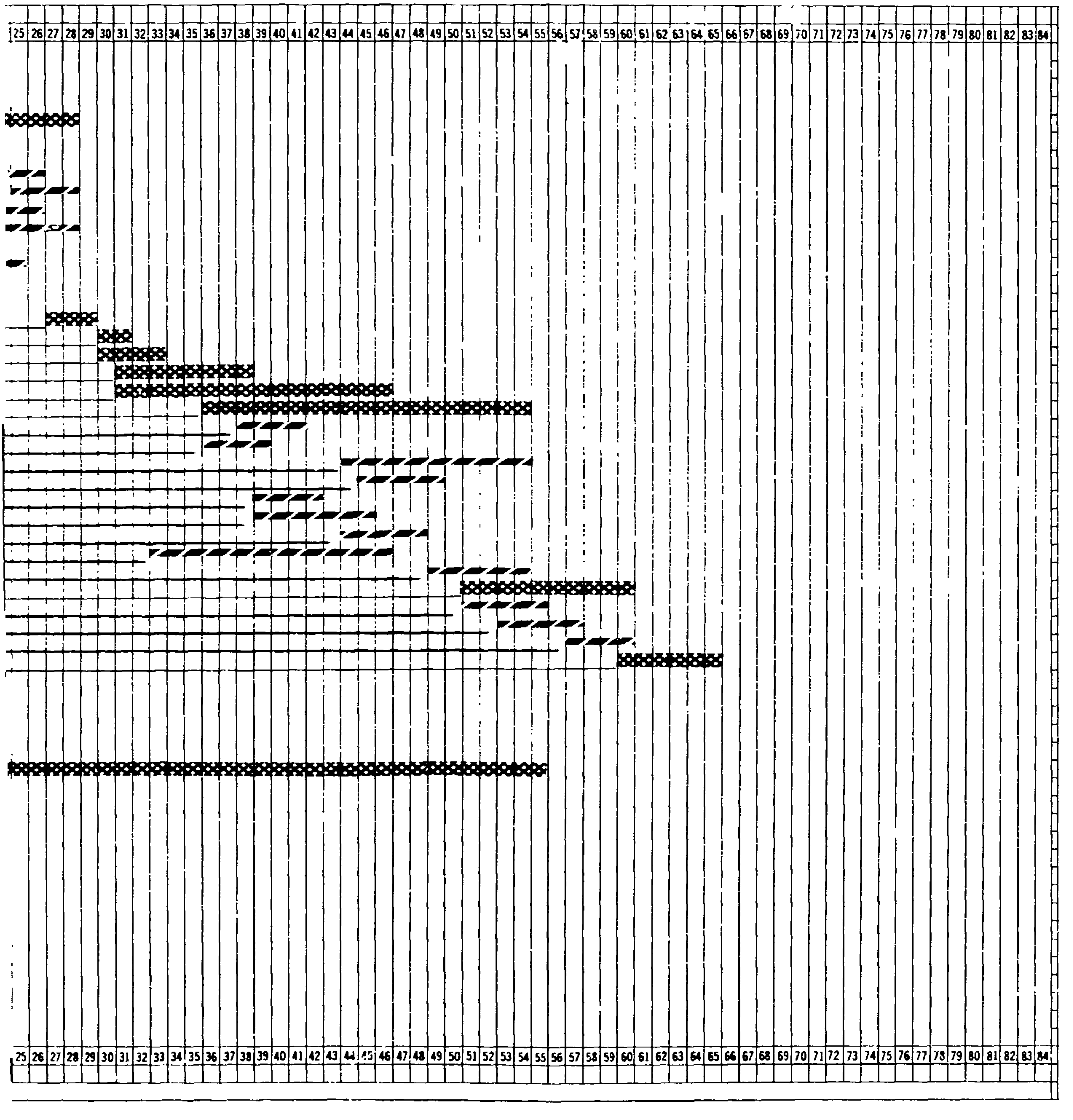
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
AFTER GO-AHEAD (MONTHS)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
CALENDAR																															

FOLDOUT FRAME 1



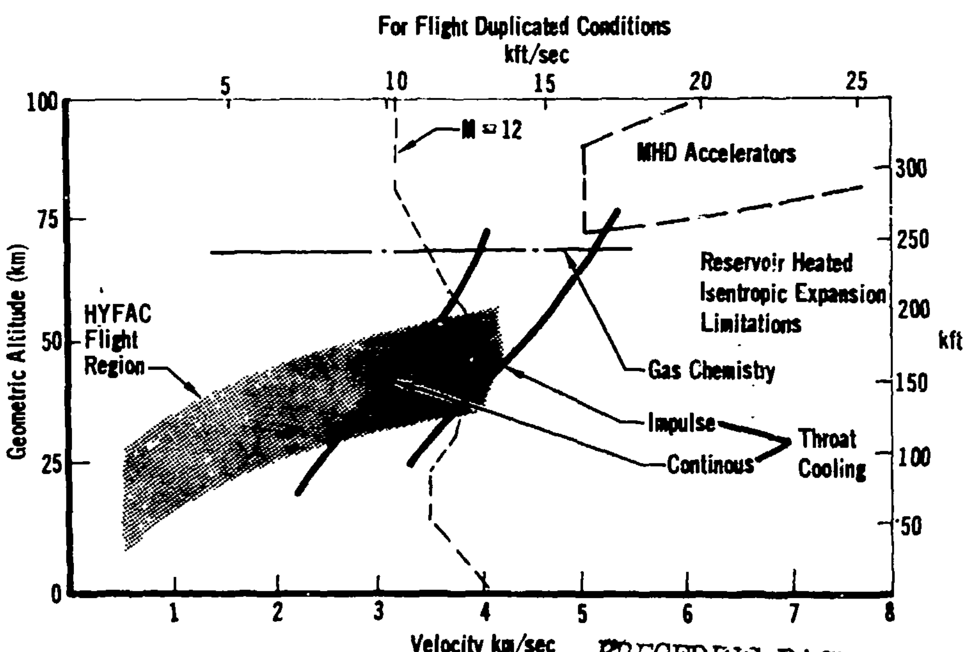
FOLDOUT FRAME 2

matrix. It appeared, therefore, feasible to increase the facility performance without increasing the storage heater size. Analysis showed that a 27.6 ft^2 (2.58 m^2) capture area module could be accommodated. This would not only permit testing of a single module representing a 600,000 lb (270,000 kg) class operational aircraft, but two to three modules representative of a research aircraft.

The facility size and mass flow represented by the Phase III definition are large enough to also perform full-scale performance and PFRT testing on turboramjet engines of the size required by the HYFAC Mach 6 research airplane. A complete operating engine (STRJ-11-A-27), which requires up to 340 lb/sec inlet flow, can be tested. The carbon fuel combustor can provide continuous duty cycle testing while pure air performance data can be obtained using the intermittent zirconia heater cycle. For a Mach 6 engine, no compromises regarding duplication of flight conditions need be made. Figure 7-27 shows the Mach 6 turboramjet installed in the scramjet test module. In addition to the removal of the specialized scramjet engine hardware, a special forward thrust-stand incorporating an adjustable nozzle similar to that used for the basic scramjet installation and an actual aircraft duct assembly must be provided.

It is felt that this Mach 6 research airplane engine test capability, in addition to the larger scramjet engine size compared to that used in Phase II, justifies the provision of the enlarged mass flow.

Unlike the gasdynamic facilities, the engine research facilities are subject to a number of limitations resulting from the high temperatures and pressures required to duplicate hypersonic flight conditions. Figure 7-2 shows the HYFAC flight corridor, and the simulation capability of E9 translated into corresponding flight conditions. Region 1 presently can only be provided by impulse f[illegible]ities employing isentropic expansion, reservoir heated techniques. Dr. Leon [illegible] of AEDC estimates that MHD accelerators will be able to provide flight dupl[illegible]d conditions at altitudes above 200,000 ft (61 km) and speeds greater than 16,000 ft/sec (5 km/sec). There is a significant region therefore, for which flight duplicated conditions cannot be provided by present facility concepts as limited by material considerations, as shown in the following sketch.



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In Figure 7-2, region (5) could be added to the E9 capability with the addition of additional compressors, exhausters, heaters, and coolers costing about an additional $90,417,000. Regions (2), (3), and (4) could be added either on an intermittent basis ($63,000,000) or on a continuous basis ($241,000,000) by employing a multi-recompression heater to supplement the basic E9 heater systems.

The concept of the modified direct connect scramjet module test section provides the capability to accommodate a full scale engine module representative of an operational aircraft using only 550 lb/sec (250 kg/sec) mass flow. In a free jet facility, about nine times that mass flow would be required to test the same module size. The concept of this test section permits duplication of the flow field from the last inlet ramp to the termination of the exhaust nozzle, as depicted in Figure 7-1.

Since this facility provides flight duplicated conditions, additional research capability can be provided by integrating an aerodynamic nozzle concept into the overall facility concept. Then the true temperature wind tunnel capability obtained can be utilized for aerothermodynamic research and evaluation of structural concepts using external flow. The thermo/structural test leg provides this capability with nozzles designed for Mach 6, 9, and 12. Although a Mach 12 nozzle is provided, the actual limit for complete flight duplication for E9 is Mach 10. Should a multi-recompression heater be added, this would become a true temperature nozzle.

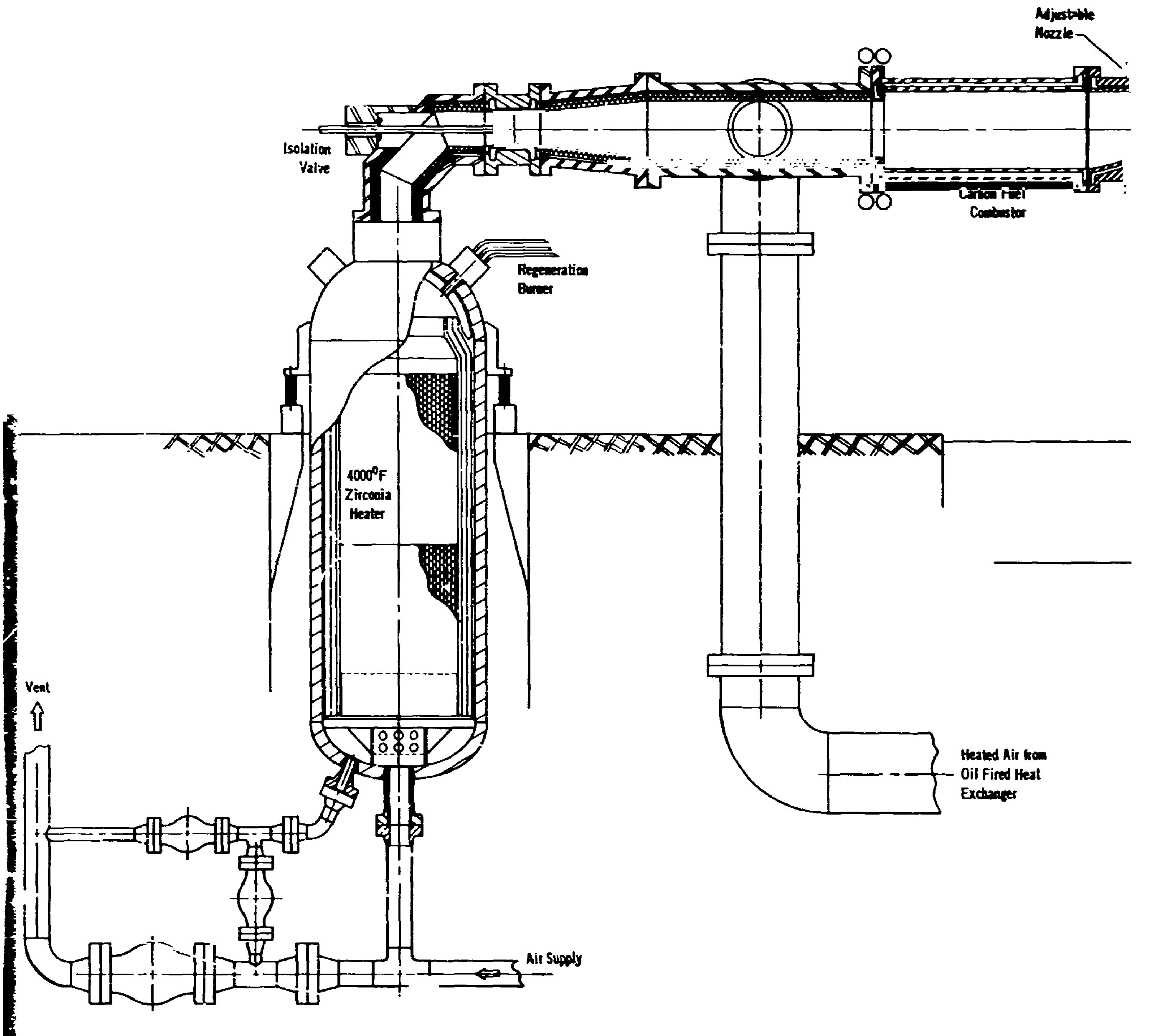
During Phase III, a final list of 278 Research Tasks, each task being a subset of the 78 Research Objectives, was defined. This list of research tasks was used to determine the research potential of each candidate research facility considered during Phase III.

E9 provides much more than just ramjet/scramjet engine research capability. Indicative of its versatility is the number of structural, operational subsystem, and thermodynamic research objectives to which E9 has applicable capability. In terms of research capability, E9 provides at least a 50% increase over existing facilities. E9 is not limited to contributing to research applicable to the HYFAC potential operational aircraft. In the areas of missiles and spacecraft, E9 could have a major contribution, as the following matrix indicates:

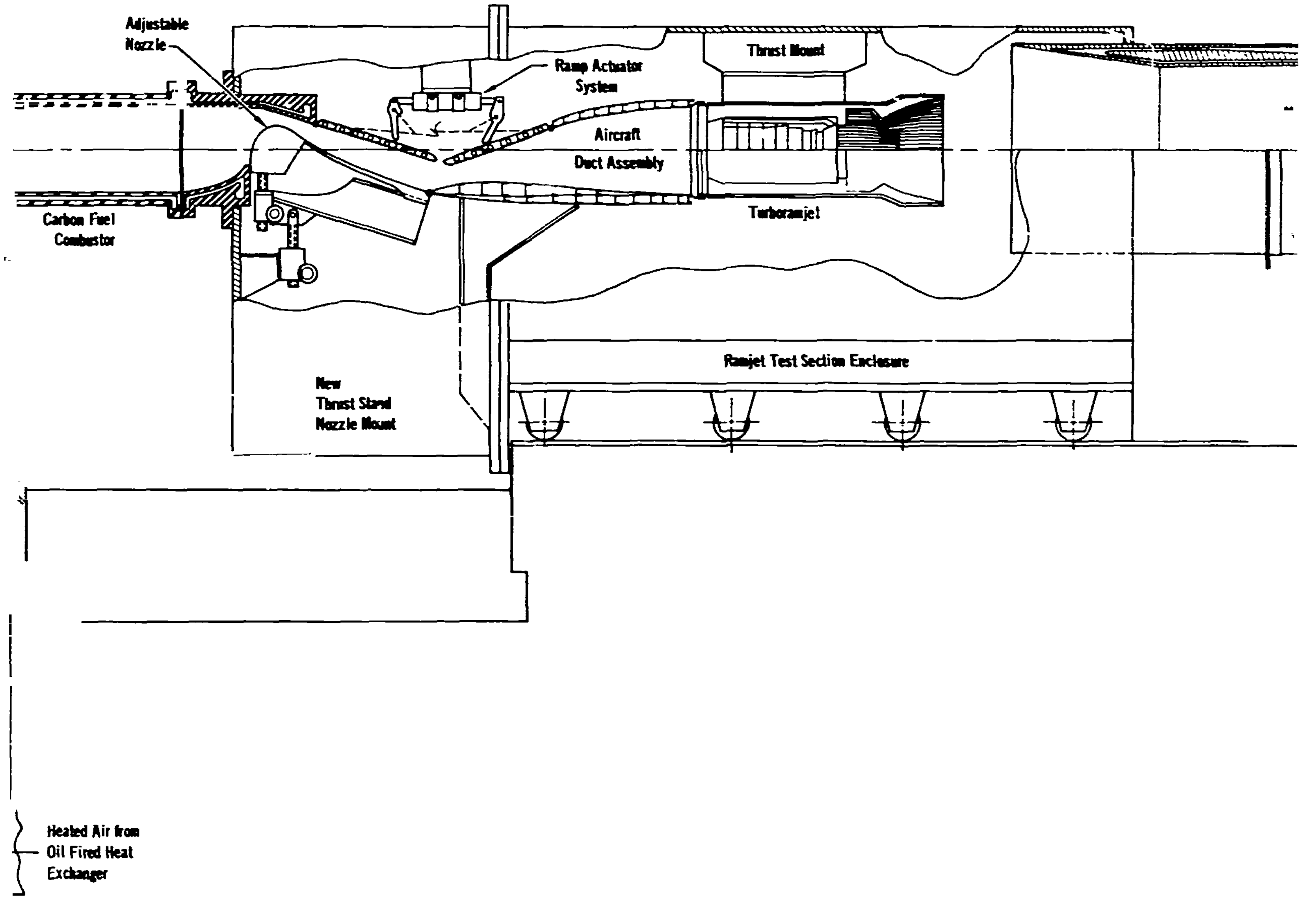
	HYFAC	TACTICAL MISSILE	INTERCEPTOR MISSILE	SPACE TRANSPORTATION SYSTEM	RE-ENTRY VEHICLES	STRATEGIC MISSILES
o ramjet engine development	●	X	X	-	-	-
o scramjet engine development	●	●	●	-	-	-
o materials research	●	●	●	●	●	X
o structural evaluations	●	●	●	●	●	●
o nozzle performance	●	●	●	●	●	-
o aerothermoelastic effects	●	●	●	●	●	●
o thermal protection systems	●	●	●	●	●	X
o thermodynamic research	●	●	●	●	●	X
o dual mode engine cycles	●	X	X	-	-	-
o gas kinetics	●	X	●	●	●	X

Contribution ● Significant
X Limited

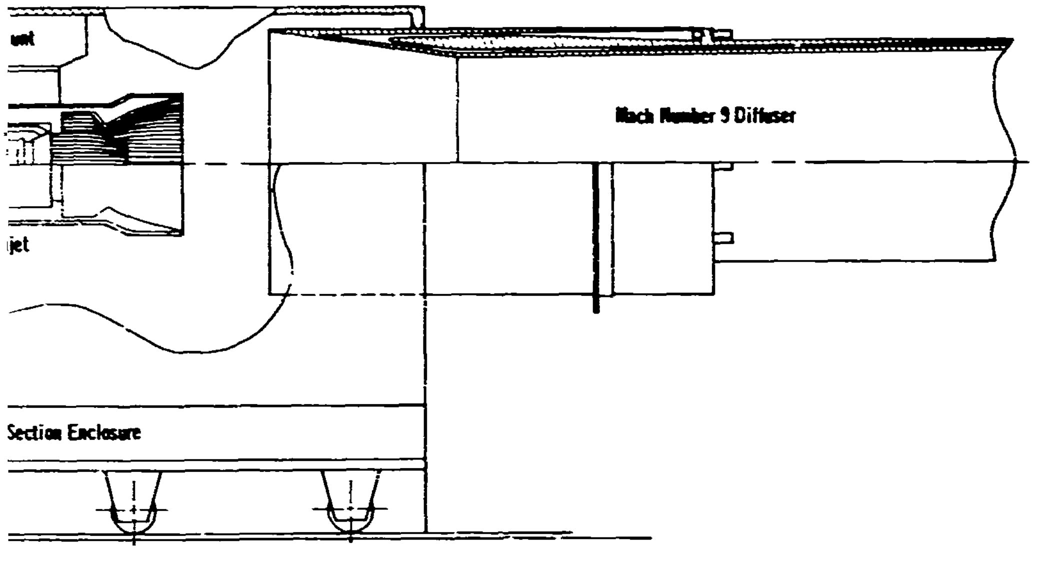
FIGURE 7-27
MODIFIED DIRECT CONNECT INSTALLATION OF TURBORAMJET ENGINE IN SCRAMJET FACILITY



FOLDOUT FRAME 1



FOLDOUT FRAME 2



FOLDOUT FRAME 3

Figure 7-28 summarizes the performance, costs, development assessment, and design characteristics of E9. The numerical confidence level associated with E9 is equal to 4.17. This numerical evaluation is consistent with the qualitative judgement that this facility represents a collection of existing concepts, already in operation at similar or slightly smaller sizes. Although integration of all these systems into a single functioning unit may require development of operational procedures, and therefore require additional time, the overall confidence that performance goals will be met is high.

This facility is unique in capability with a dual mode of operation, i.e., continuous and intermittent. This concept, combined with the test conditions available, allows scramjet testing on a real time trajectory, which has the advantage of heating the structural materials of the test article in a manner identical to the flight case.

Considering the versatility, research capability applicable to HYFAC type aircraft as well as other aircraft systems, moderate cost, and good confidence of achieving the specified performance, it would appear that the advent of large, air-breathing, operational hypersonic aircraft would be predicated on the acquisition of a research facility analogous to E9.

7.7 MODIFICATION OF EXISTING FACILITY FOR RESEARCH ENGINE TESTING

Research aircraft sized SJ and CSJ engines can be tested in facilities having considerably less capability than E9.

The VKF complex at AEDC currently has a great deal of the equipment and services necessary to create a small scale version of E9. Figure 7-29 illustrates the facility and shows a scramjet test leg added to the existing plant.

For SJ testing, a very capable facility can be created by the addition of a smaller version of the E9 scramjet module, a carbon combustor with carbon and oxygen supply, and dehumidification cooling equipment. This facility would have the following specifications:

Mach	10.5
Mass Flow	115 lb/sec (52.3 kg/sec)
Stagnation Pressure	3000 psia (2070 N/cm^2)
Stagnation Temperature	7000°R (3900°K)
Run Time	Continuous

The cost of such a modification is estimated to be $15 million.

Convertible scramjet engine testing of similar modules will require approximately double the mass flow in order to duplicate conditions at the lower range of flight Mach numbers. For this testing, in addition to the equipment listed above, another compressor plant like the VKF must be added. Also required are additional dehumidification coolers and an additional combustion heater system. Such a facility would have the same pressure and temperature as the smaller SJ facility modification, and 230 lb/sec (104.6 kg/sec) mass flow. Its cost is estimated to be $30 million.

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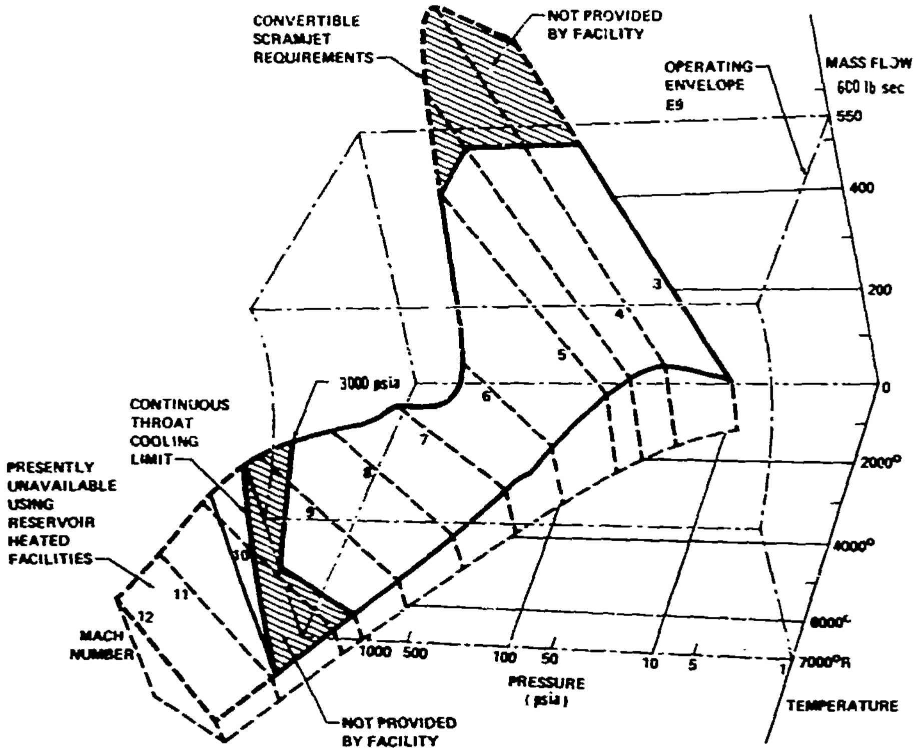
FIGURE 7-28
PERFORMANCE AND SPECIFICATIONS FOR E9



SCRAMJET TEST SECTION
ENGINE MODULE SIZE

1 Module: 16 in (0.41 m) high x 45 in (1.15 m) wide
Modules: 8.7 in (0.22 m) high x 86 in (2.18 m) wide
3 Modules: 5.1 in (0.13 m) high x 142 in (3.60 m) wide

THERMO/STRUCTURAL LEG

Mach Number	Constant Velocity Core Diameter ft (m)	Nozzle Exit Diameter ft (m)
6	5.7 (1.74)	6.45 (1.97)
9	8.8 (2.69)	12.2 (3.72)
12	9.0 (2.75)	18.6 (5.67)

NOZZLE SIZE

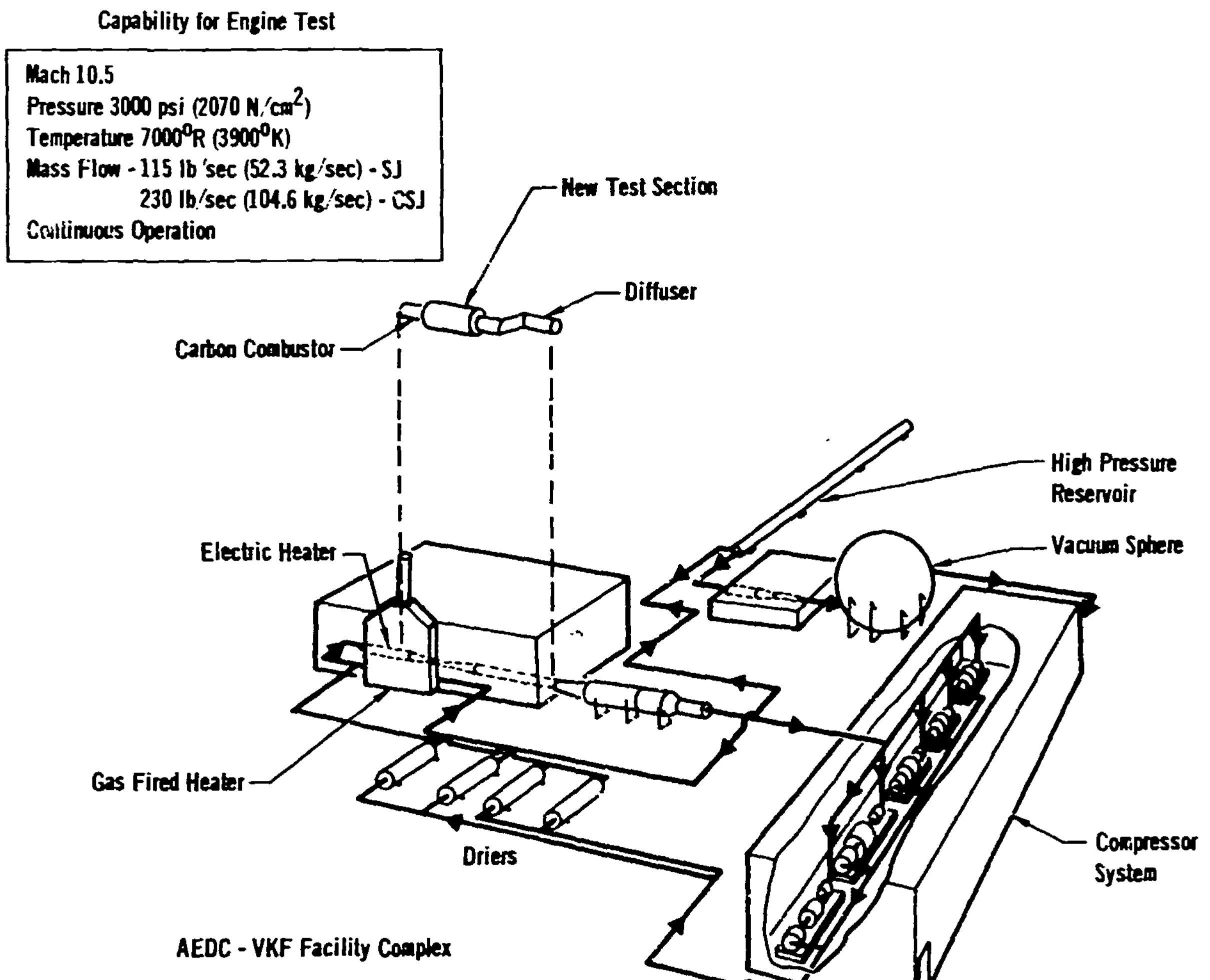
800 in^2 (.515 m^2) Potential Flow Area

Nominal Size: 19.1 in (.486 m) high x 49.5 (1.26 m) long

Cost - $147,085,000

Confidence level.
4.17 on a scale from 1 to 5, where 5 represents low risk existing equipment technology, and 1 represents high risk theoretically predicted technology.

FIGURE 7-29
VKF MODIFICATION FOR RESEARCH SCRAMJETS AND CONVERTIBLE SCRAMJETS



8. STRUCTURES RESEARCH FACILITIES (S20)

The development of an operational hypersonic vehicle will require extensive ground testing to verify and prove the materials and structural design. The testing technology developed for spacecraft will have to be employed on a larger scale to prove the hypersonic aircraft. Existing facilities capable of duplicating the environments experienced by spacecraft and hypersonic vehicle cannot test specimens of the size required for proving an operational hypersonic vehicle. Thus, a requirement for new structural ground test facilities to test the bigger specimens under severe environmental conditions does exist.

In Phase I, 26 non-flow ground test facilities were investigated that offered complete testing capability for all types of ground non-flow testing required for a hypersonic vehicle. Nine structural test facilities were included in this initial group. The Dynamic Structural Evaluation Facility (S2) was chosen as the baseline facility because it provided the widest range of testing capability. Due to the similarity between the various structural facilities, the capability of S2 could be upgraded to perform the functions of other facilities by adding certain types of unique test equipment. Without major modifications, the fuel flow system in S2 could serve the functions of the entire Fluid Facility. Thus a versatile ground test facility was developed that could perform a majority of the functions outlined by all the structural and fluid facilities in Phase I.

Further refinement was needed in the facility design to give the most practical facility to efficiently perform the most important types of structural testing. Basically, three types of structural testing will be required: (1) development testing of structural concepts, (2) ultimate strength verification, and (3) design life verification. Certain types of fluid flow and slosh tests are also required.

The primary factor that affects facility design and cost is the size of largest anticipated test article. The various types of test specimens that may be considered are shown in Figure 8-1 and are described in detail in Figure 8-2 . The optimum test article is that which will yield the highest level of confidence with the least cost. A major section is large enough to accommodate structural and thermal interactions that may be present under structural fatigue and transient heating testing. The precise size of the test article will depend on the actual operational design and the equipment required to test the specimen will depend on its size. Even though the S20 facility was sized to test major sections, certain types of room temperature and ambient pressure tests can be performed on full-scale airframes. An additional benefit is derived from sizing the baseline test article as a major section, because the same facility is capable of testing a complete research vehicle.

8.1 REFINEMENTS IN DESIGN AND PERFORMANCE

The facility description which resulted from the Phase II parametric evaluation was considered well defined in terms of equipment specifications and requirements. The refinements made in Phase III emphasized definition of a realistic structural research complex with the integration of a hazardous remote site for experiments with fueled test articles. Existing test track facilities were reviewed to determine if they were sufficient to accomplish the research associated with horizontal tank acceleration or whether a new facility would be necessary.

FIGURE 8–1
REPRESENTATIVE STRUCTURAL ELEMENTS
OF A HYPERSONIC AIRCRAFT

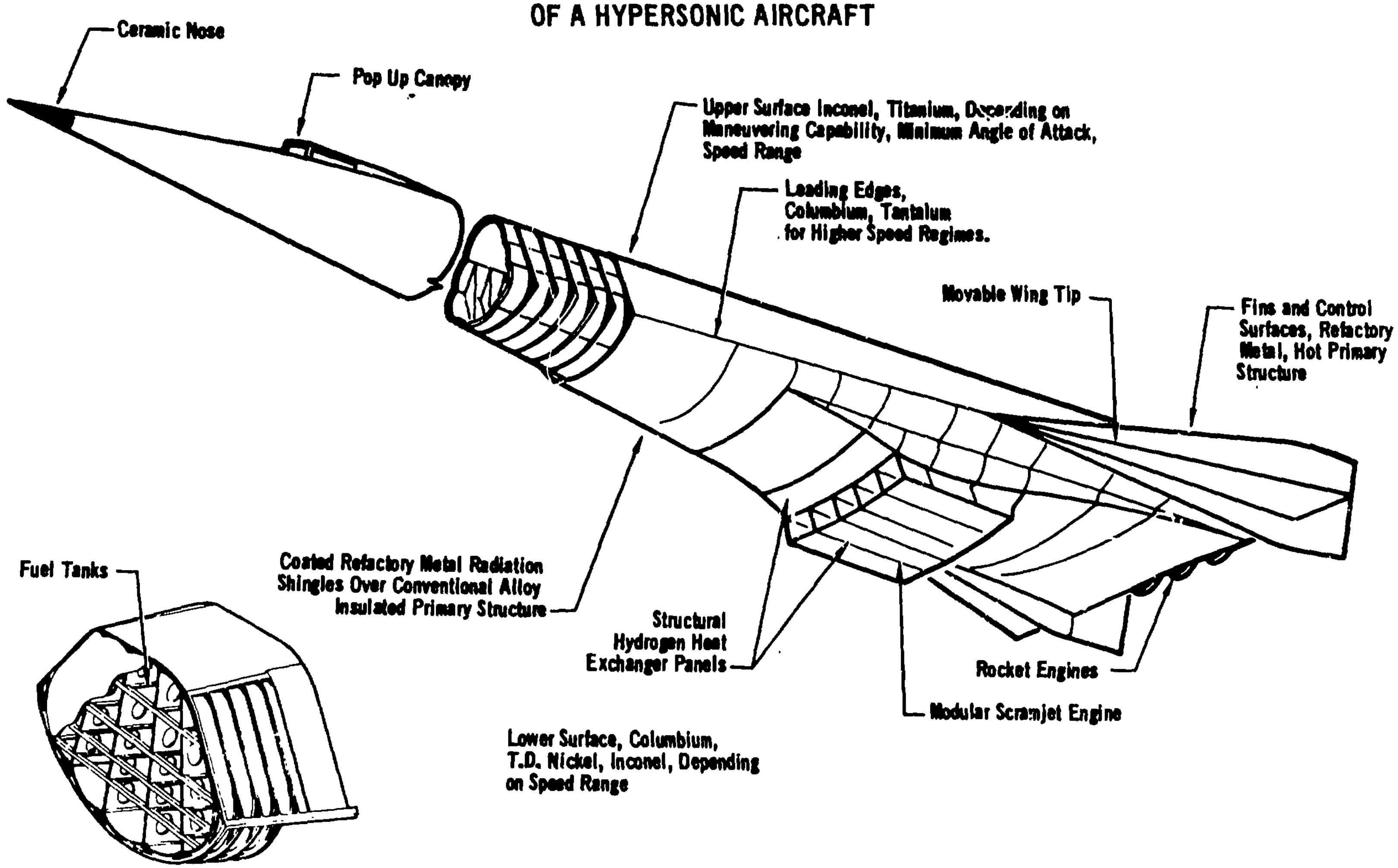
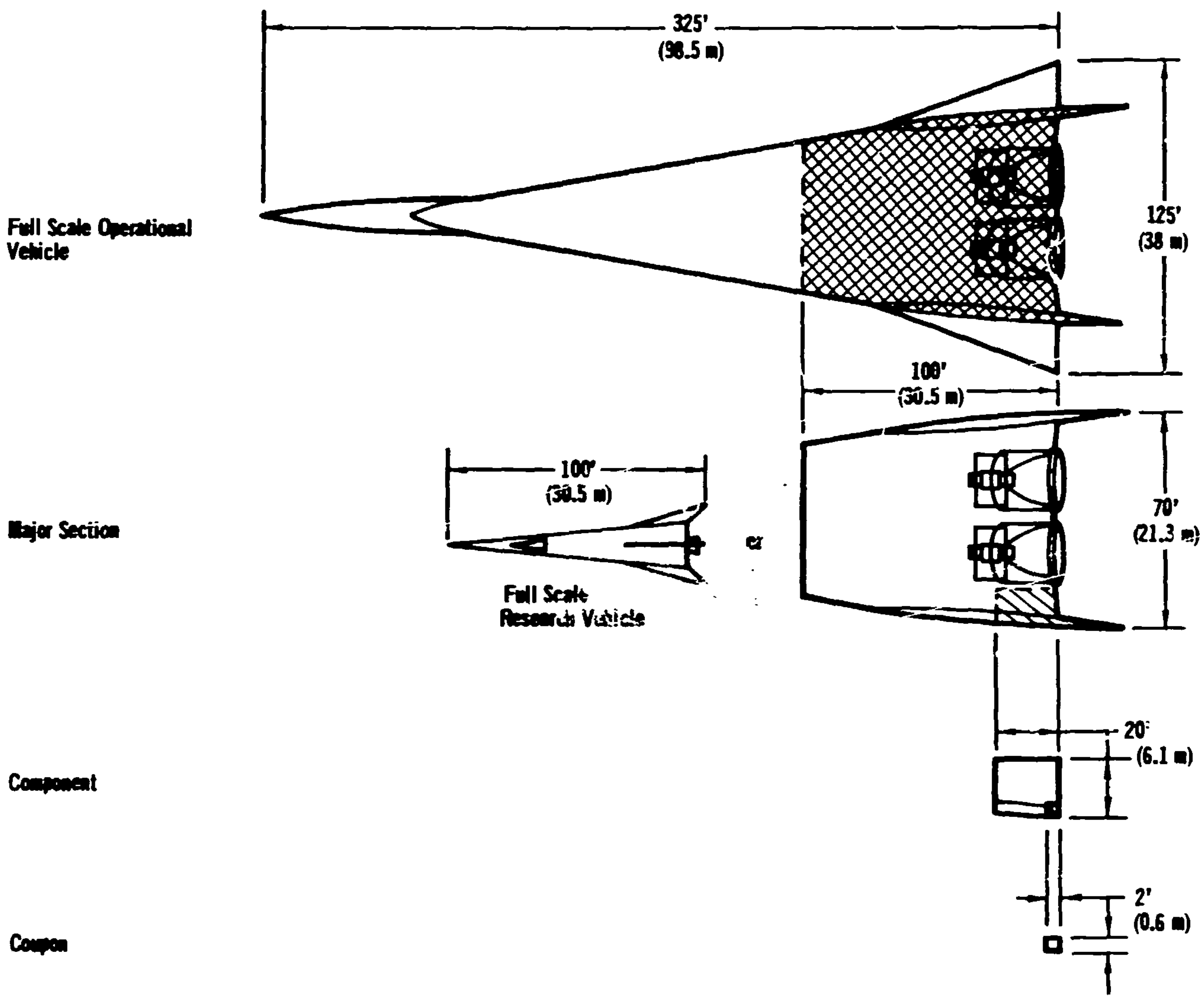


FIGURE 8-2
TEST ARTICLE SIZE



8.2 FACILITY DESCRIPTION AND COSTS

The structural test complex will consist of 3 facilities, (1) structural laboratory, (2) hazardous fuel test areas, and (3) fuel slosh test track. An overall view of the structural laboratory and fuel test area is shown in Figure 8-5. The structural test lab will consist of a high bay test area that incorporates a structurally reinforced floor. Test equipment was provided to duplicate mechanical loads, vibration, thermal, attitude, acoustic, and thermal-acoustic environments. A sketch of a typical layout for the structural test lab is shown in Figure 8-3 .

A remote site cryogenic fuel test area (Figure 8-4) is required to test: (1) fuel tank thermal protection systems, (2) cryogenic fuel usage, (3) cryogenic heat exchangers, and (4) rapid refueling techniques. The facility must contain adequate cryogenic and hydrocarbon fuel storage and transfer capability so that representatively sized fuel tank and structural specimens may be used. Flow-rates approaching 60,000 gpm (3.78 m^3/sec) must be provided for cryogenic fuels and slush hydrogen to simulate the rapid refueling times required for military vehicles. The facility will consist of a structurally reinforced floor covered by a weather protection shell. The facility will be surrounded by an earthen revertment to protect personnel and to contain a cryogenic fuel spill. The basic environments or conditions duplicated by the facility include fuel flow, thermal, and mechanical loads.

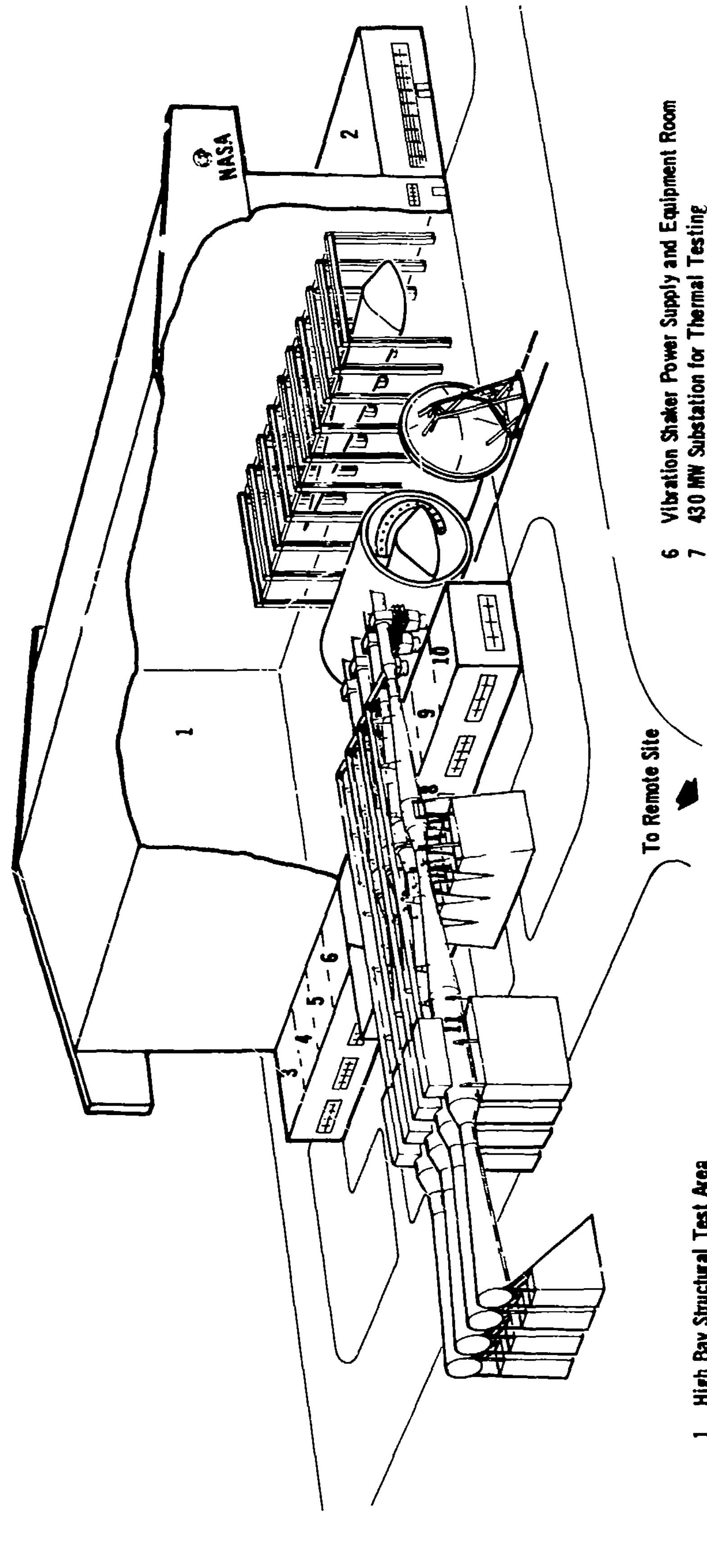
The approach taken with respect to the remote facility concept is to have the fuel facility located in relative close proximity (10,000 ft or 3048 m) from the structural laboratory so that common electrical power generators, data acquisition system, and test personnel may be used. According to the range safety practices of the Air Force Eastern Test Range, a cleared area of a 10,000 ft (3048 m) radius would provide adequate protection in the event of a massive cryogenic spill and resulting fire. The remote site concept is shown in Figure 8-5 .

The slosh test track will subject realistically sized tank configurations to sustained acceleration combined with random vibration simulating takeoff roll and vibration, aerodynamic maneuvers, and thrust cutoff. These test tanks must be subjected to sustained accelerations for sufficient time to develop final or steady state slosh characteristics. Four seconds of actual test time was considered the minimum acceptable test time and more time would, of course, be desirable.

Centrifuges and rocket sleds are the two methods that are available to subject test specimens to sustained acceleration. Centrifuges can satisfactorily test relatively small test articles, but for larger specimens or rapid changes in acceleration, the rocket sled appears to be the only practical method of duplicating sustained acceleration. Acceleration changes may be accomplished on a rocket sled by varying the rocket thrust, terminating thrust, or using water brakes. The acceleration of a centrifuge may only be varied by changing the torque on the radius arm which is difficult to measure and control.

A search of existing sled track facilities revealed that the Test Track Facility at Holloman AFB, New Mexico could fulfill the majority of slosh testing required for a hypersonic vehicle development program. The Holloman track is capable of supporting sled weights to 16,000 pounds (7300 kg), which would be adequate for

FIGURE 8-3
PHYSICAL ARRANGEMENT S20 FACILITY



1 High Bay Structural Test Area
2 Offices
3 Acoustic Research Cell
4 Vibration and Acoustic Control Room
5 Thermal/Acoustic Research Cell
6 Vibration Shaker Power Supply and Equipment Room
7 430 MW Substation for Thermal Testing
8 Mechanical Equipment Room
9 Altitude Chamber Control Room
10 Steam Ejector Control Room
11 Chemical Steam Ejector for Altitude Chamber

FIGURE 8–4
REMOTE HAZARDOUS FUEL TEST AREA

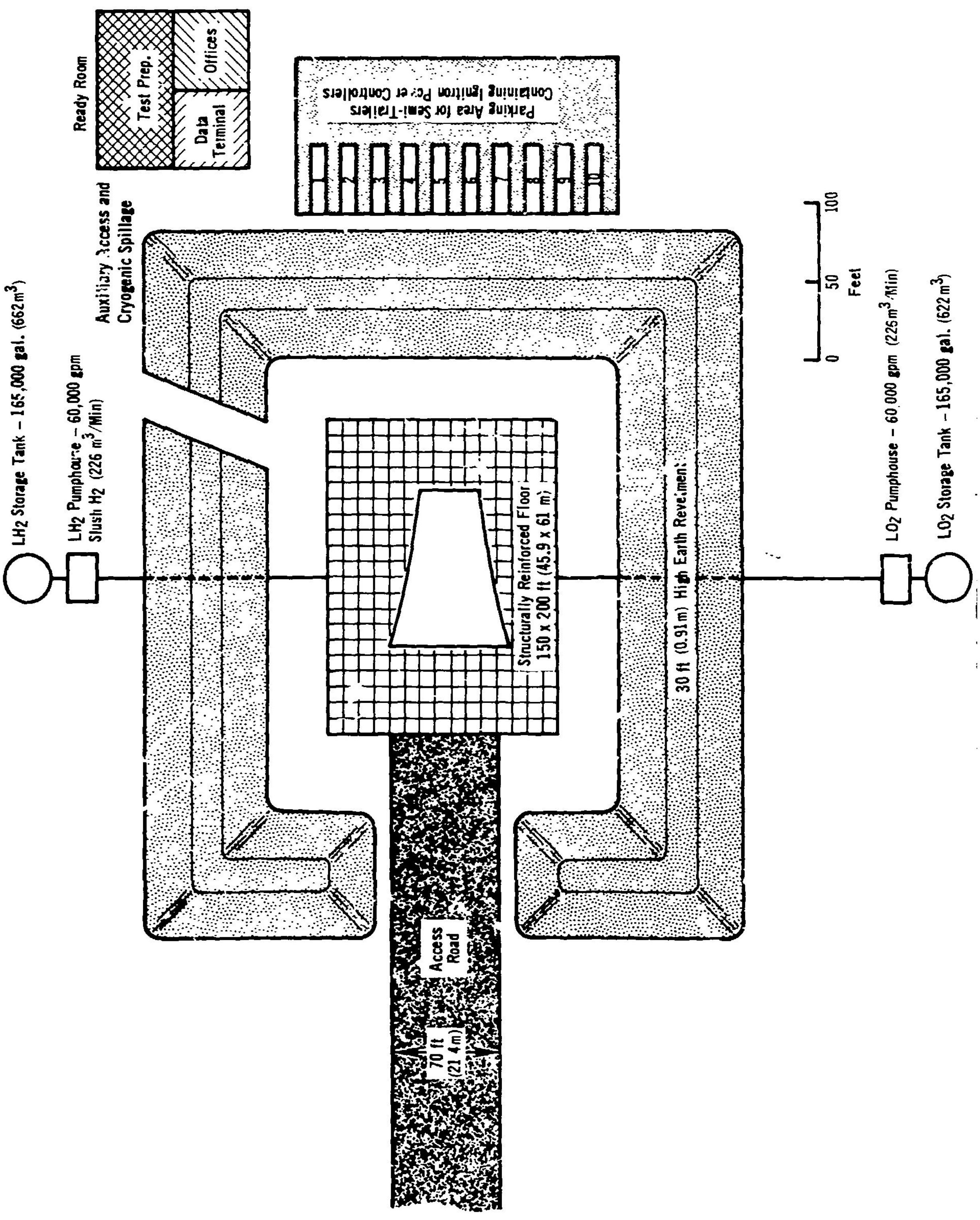
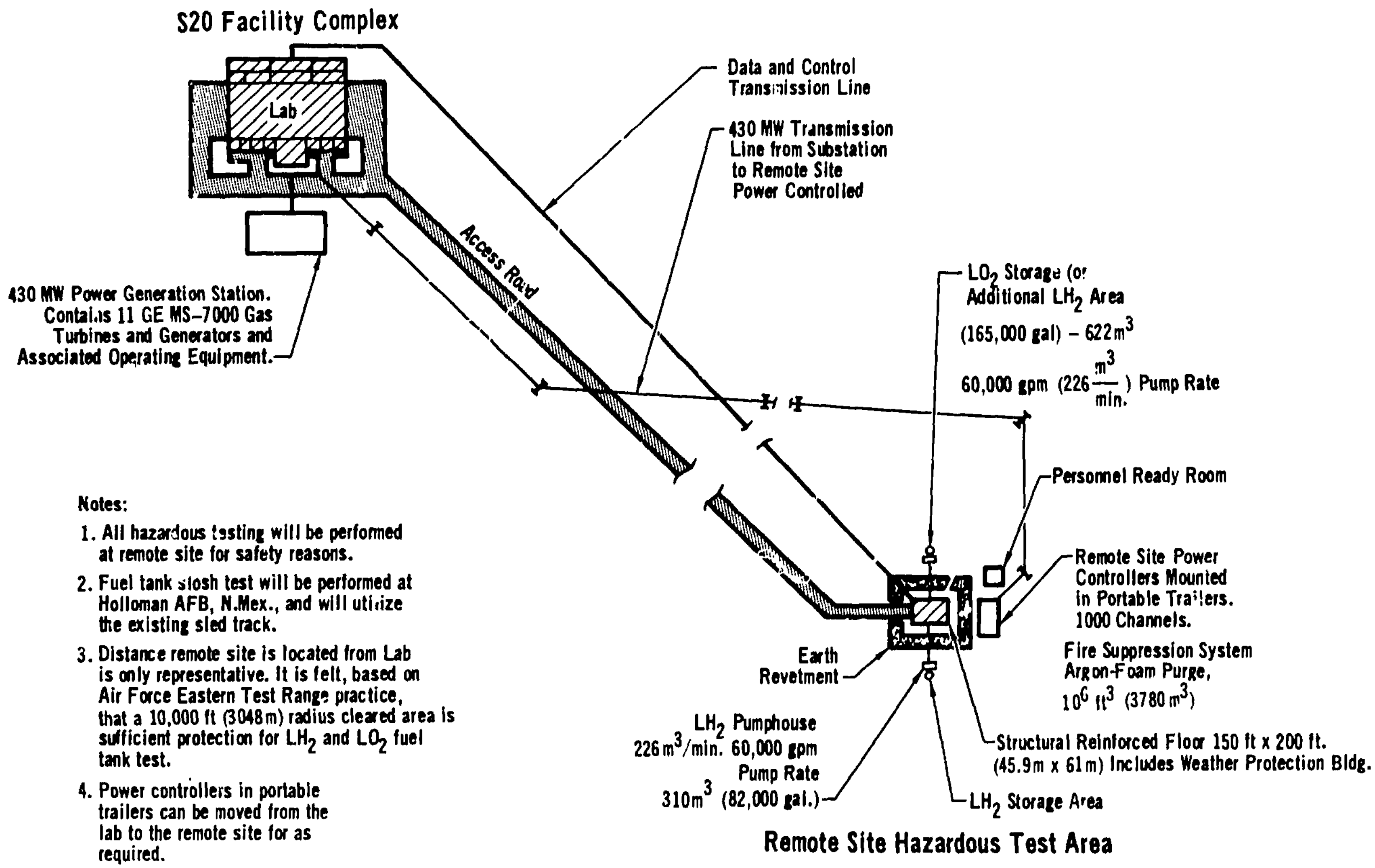


FIGURE 8–5

REMOTE HAZARDOUS TEST SITE IN RELATIONSHIP TO MAIN LABORATORY AREA



Notes:

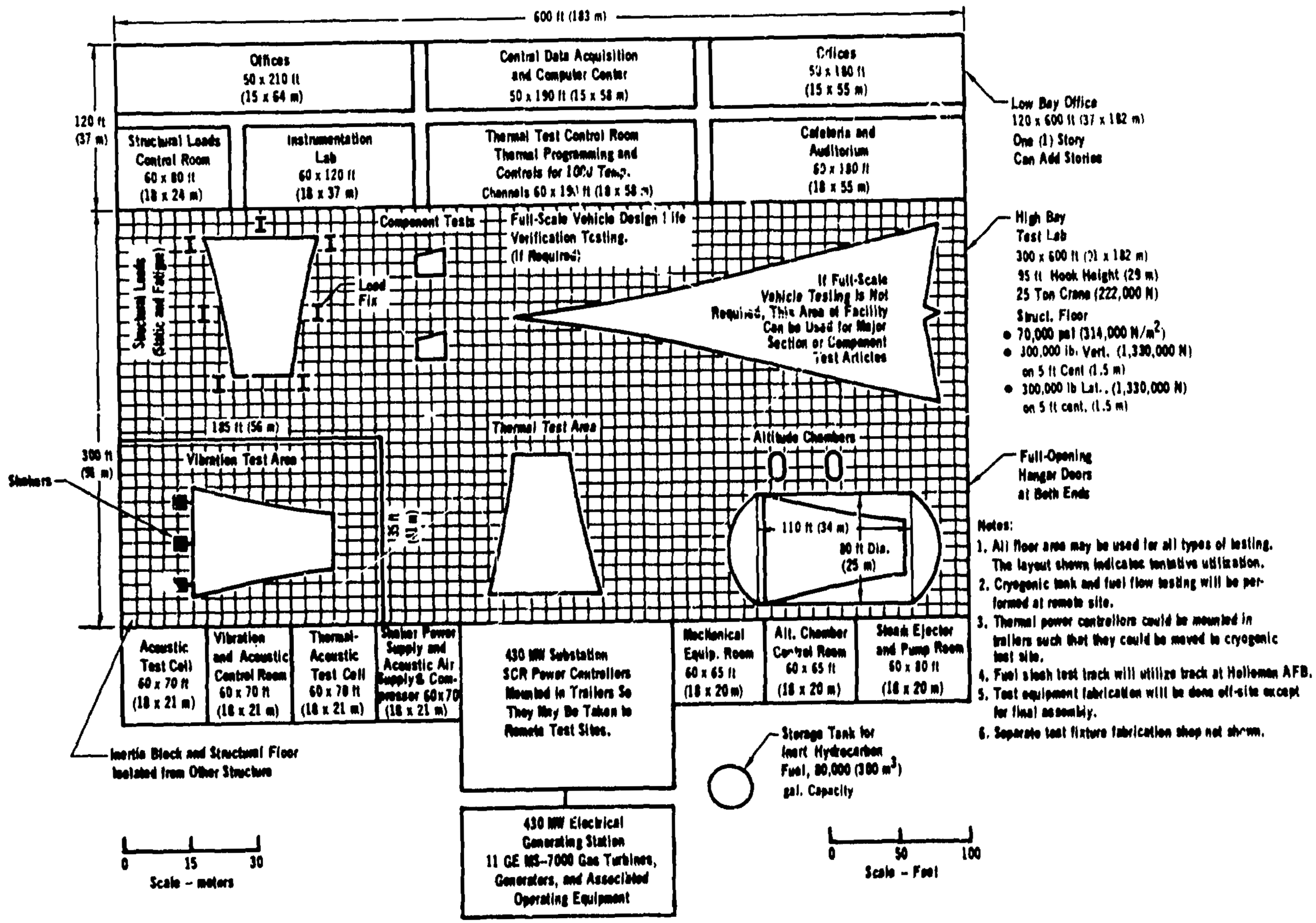
1. All hazardous testing will be performed at remote site for safety reasons.
2. Fuel tank slosh test will be performed at Holloman AFB, N.Mex., and will utilize the existing sled track.
3. Distance remote site is located from Lab is only representative. It is felt, based on Air Force Eastern Test Range practice, that a 10,000 ft (3048m) radius cleared area is sufficient protection for LH_2 and LO_2 fuel tank test.
4. Power controllers in portable trailers can be moved from the lab to the remote site for as required.

testing full-size LH_2 tanks and subscale LO_2 and hydrocarbon fuel tanks. The track length is sufficient to allow test times of 16 seconds of sustained 3g acceleration, with an equal amount of time for deceleration. Fuel flow could be accomplished by burning the fuel in a suitable rocket motor or pumping it into on-board storage tanks at a predetermined rate. A special sled would be constructed to contain the tank, rocket motors, vibration exciter, and telemetry instrumentation.

The general arrangement of the main laboratory building is shown in Figure 8-6. Most of the equipment and performance capabilities defined in Phase II were carried into Phase III with only minor adjustments. The rationale and criteria to establish these capabilities are well documented in Volume III. In summary, the performance of S20 in terms of the equipment specifications is:

	UNITS	PARAMETER CAPABILITY
THERMAL SYSTEM		
Max. Heat Flux 50 ft^2 (4.65 m^2)	Btu/ft^2-sec (kW/m^2)	500 (5680)
Avg. Heat Flux	Btu/ft^2-sec (kW/m^2)	40 (372)
Total Available Power	MW	430
Number of Control Channels		1000
Heating Rates Obtainable	°F/sec (°C/sec)	0 to 30 (0 to 16.7)
ALTITUDE		
Altitude Chamber volume	ft^3 (m^3)	5×10^5 (14.15×10^3)
Maximum Altitude	kft (km)	68 (21)
Time to Altitude	sec	1.8
ACOUSTIC		
Acoustic Sound Pressure Level	dB	170
Total Acoustic Power	acoustic watts	4.8×10^6
Acoustic Frequency	Hz	15-10,000
Number of Acoustic Generators		160
MECHANICAL LOADS		
Number of Mechanical Load Channels		200
Max. Load/Channel	lb (N)	50,000 (222,000)
Max. Loading Rate	lb/sec (N/sec)	400,000 (1,778,000)
Cycling Rate	Hz	0 to 5
MECHANICAL VIBRATION		
Number of Mechanical Shakers - 30,000 lb (133,100 N)		20
Frequency Range	Hz	30-3000

FIGURE 8-6
GENERAL ARRANGEMENT MAIN LABORATORY COMPLEX, S20



FUEL FLOW		
Cryogenic Fuel Tankage & Control System	ft^3 (m^3)	50,000 (1410)
Cryogenic Pumping	gpm (m^3/min)	60,000 (264)
FUEL SLOSH ACCELERATION TRACK		
Length	ft (m)	1500 (457)
Maximum Acceleration	g	3 4
Test Time	sec	16 13

S20 was sized to accomodate a major section of an operational aircraft, and requires about 430 MW of power. As a comparison, the simulation requirements for thermal simulation only for the complete operational aircraft is given in Figure 8-7. The magnitude of the task to provide this capability in an actual experimental situation is the reason costs are so high for combined altitude/mechanical/thermal simulation for very large structures. In an actual situation, even the size of the major section selected for the Phase III refinements will undergo variations depending on technical risks versus costs. The cost summary for the amin laboratory complex and remote hazardous test site is presented in Figure 8-8. The relative distribution of the costs are given in the pie charts in Figures 8-9 and 8-10. The structural test building, thermal test equipment and electrical substation comprise the major cost expenditures. As indicated in Figure 8-10, the hazardous test area represents a significant cost increment.

Because of the multitude of variations in tests which may be possible, as well as test article size, identification of a unique operational cost is very difficult. A first order estimate for the occupancy charges would be.

ENERGY	$1370
CONSUMABLES	200
MAINTENANCE	200
STAFFING	2800
	$4570/OCCUPANCY HOUR

This conglomerate cost would approximate operation of the entire facility complex with 60% of its 8 research areas occupied, and 80% of the maximum power utilized. Specific costs for a given structural program would have to be estimated on an individual basis. This does indicate the overall level of monitary support necessary for the S20 complex.

These costs were based on techniques presented in Section 2 of Volume III and Volume IV.

8.3 SPECIFIC SITE CONSIDERATIONS

The additions of the remote hazardous test area imposes some restriction of the site chosen for S20. The close proximity of population centers would probably rule out the location of such large quantities of liquid oxygen and hydrogen in a facility

FIGURE 8–7
HEATER REQUIREMENTS FOR FULL-SCALE VEHICLE

TYPE OF STRUCTURE	ASSUMED PERCENT OF SURFACE AREA	AREA		TEMPERATURE		FLUX *		TOTAL POWER	CONTROL ZONE SIZE		NUMBER OF CONTROL ZONES**
UNITS	%	ft^2	m^2	°F	°C	Btu/ft^2-sec	kW/m^2	kW	ft^2	m^2	-
Nose Cap	3	1,200	111	3500	1950	170	1930	2.2×10^5	2.5	.23	460
Leading Edge	17	7,000	650	3000	1780	97	1100	7.2×10^5	4.5	.42	1500
Lower Body and Control Surfaces	40	16,400	1520	2000	1110	31	352	5.1×10^5	18	1.67	1060
Upper Body	40	16,500	1630	1600	880	20	227	3.8×10^5	35	3.24	790
TOTAL		41,000	3801					1.8×10^6			3810

* Flux based on 65% heater efficiency and 30°F (16.7°C)/sec heating rate

** 480 KVA/channel

FIGURE 8-8
COST SUMMARY – S20

Sheet 1 of 2

Facility Component	Cost ($1000's)
Structures Laboratory	
Building Complex	
Structural test area	28,039
Office area	2,196
Miscellaneous test cells and utility rooms	852
Miscellaneous control rooms	290
Shop and fabrication area	946
Subtotal Building Complex	32,323
Equipment	
Shop equipment	1,605
Thermal test equipment (including programmers, controllers, regulators, and heaters)	52,874
Structural loading system (including servos, load cylinders, and hydraulic pumps)	1,018
Vibration exciters and controls	4,200
Acoustic generators	135
Environmental chamber 80' Dia x 110' Long (24.4 m Dia x 38.6 m)	1,280
Environmental chamber 10' Dia x 20' Long (3.05 m Dia x 6.1 m Long)	600
General purpose test equipment	1,610
Subtotal Equipment	63,322
Instrumentation	
Test control complex	3,000
Data acquisition - 3000 channels	3,000
Transducers - 4500 units	1,125
Subtotal Instrumentation	7,125
Services and Utilities	
Compressed air	5,900
Water	800
Cryogenics (LH_2, LN_2, LO_2) supply	6,600
Fuel (JP-4) supply	320
Substation (GE MS-7000 Gas Turbines, switch gear and transformation)	33,000
LO_2/alcohol altitude simulation system	4,700
Boiler plant	150
Subtotal Services and Utilities	51,470
Subtotal Structures Laboratory	154,240

FIGURE 8-8 (Continued)
COST SUMMARY – S20

Sheet 2 of 2

Facility Component	Cost ($1000's)
Hazardous Test Area	
Test pod with revetment and shelter	12,145
Blockhouse	3,100
Taxiway - 10,000 feet	10,278
Parking apron	7
Cryogenics (LH_2, LO_2) supply	10,524
Substation (transmission line and transformers)	1,080
Data transmission hardline - 4000 channels	6,400
Subtotal Hazardous Test Area	43,534
Total S20 Components	197,774
Contingency @ 10%	19,777
Total S20 Facility Cost	217,551
A & E Fee @ 6%	13,100
Management and Construction Coordination Fee @ 4%	8,700
Grand Total S20	239,351

FIGURE 8-9
STRUCTURAL TEST FACILITY COST COMPARISONS
Total Acquisition Cost: $239,351,000

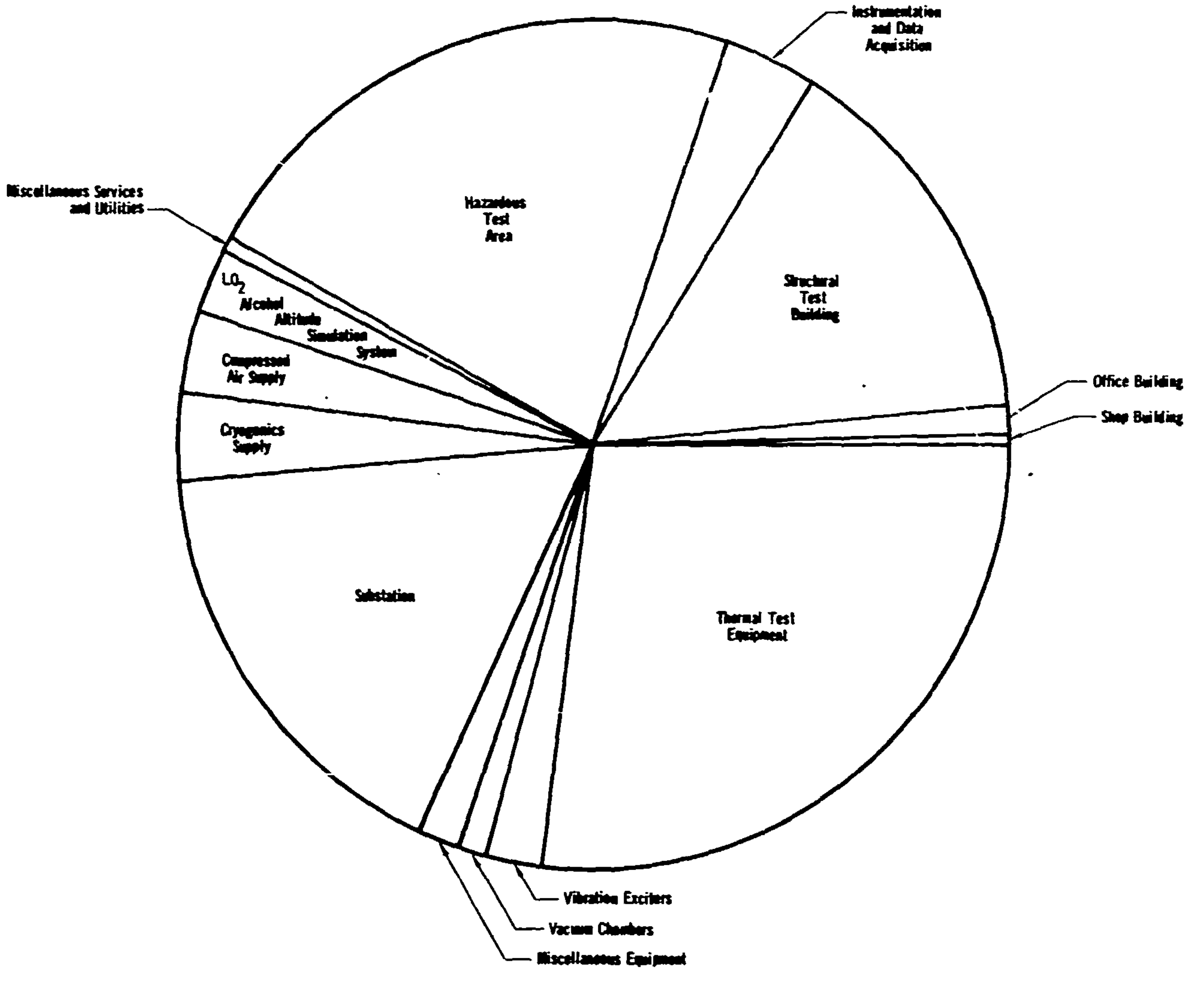
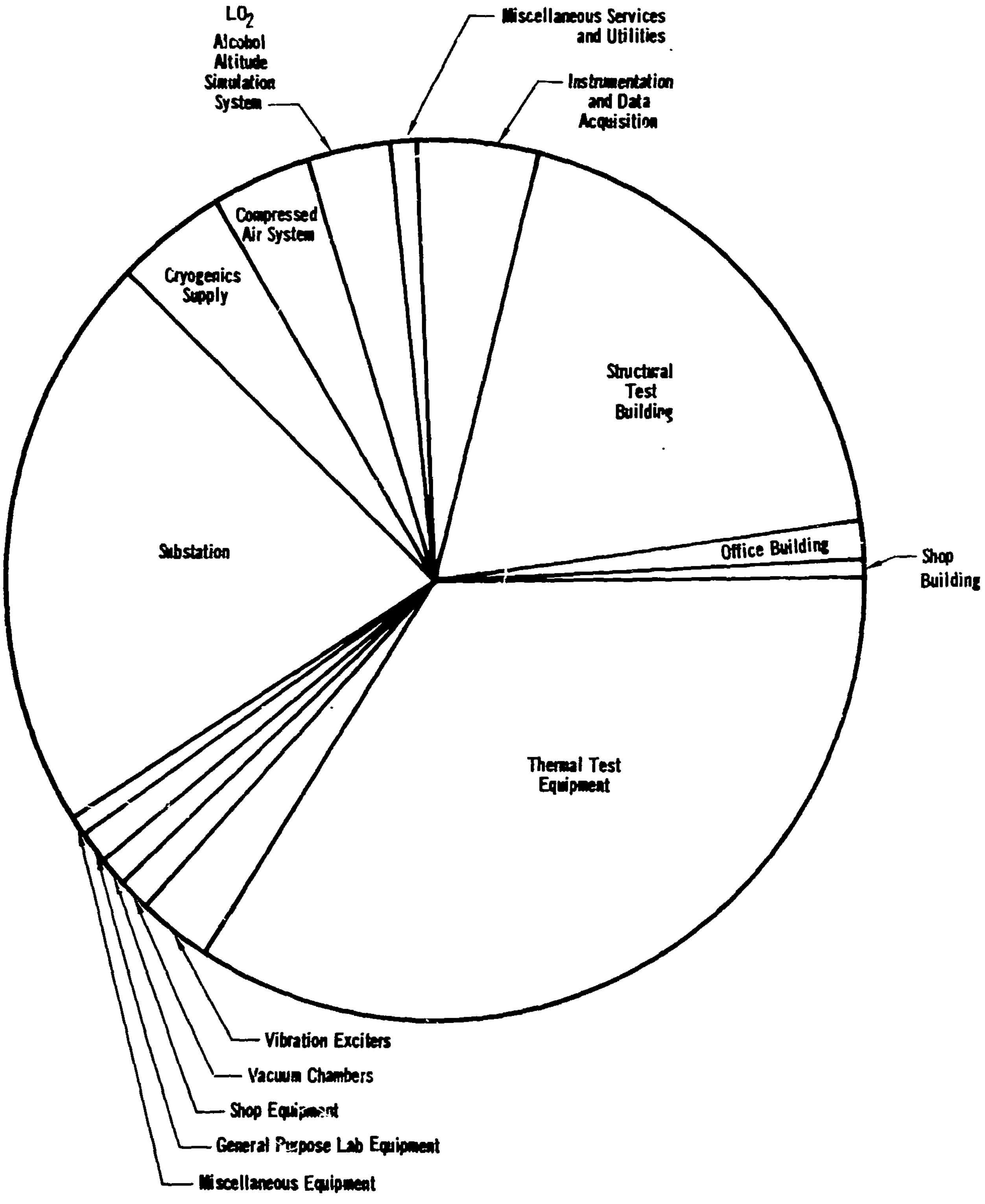


FIGURE 8-10
ACQUISITION COST BREAKDOWN FOR S20 LESS HAZARDOUS TEST AREA
Total Acquisition Cost: $186,630,000



which has the tank specimens at surface temperatures exceeding 2000°R (1100°K). The main laboratory complex could probably be integrated into any existing large structural laboratory complex such as Langley Research Center. If a proper bearing strength floor can be obtained for the soil conditions associated with coastal tidewater areas, Langley would probably offer a suitable site for even the remote site. Perhaps Wallops Island may prove a feasible location for such a site. Other than this specific consideration, the general considerations in Section 2.7 apply.

8.4 DEVELOPMENT ASSESSMENT

The general rules for the development assessment are presented in Section 2.4. Individual component assessments and costs are summarized in this section. The following table lists the individual facility elements, cost factor and confidence level evaluation.

Item	Cost Fraction (Ki)	Confidence Level (C_{Li})	$K_iC_{L_i}$	Per Cent Technical Risk	Technical Risk Ranking
Building Complex	.16	5	.80	10.67	4
Thermal Equipment	.27	4	1.08	36.02	1
Test Equipment	.05	5	.25	3.34	5
Instrumentation	.03	5	.15	2.00	6
Utilities	.26	5	1.30	17.34	3
Hazardous Area	.23	4	.92	30.68	2
Totals	1.00		4.50	100.00	

The high confidence level of 4.50 is indicative of the use of existing structural laboratory equipment in making up the S20 facility. The major challenge will not be the construction of the facility, but rather the design and organization of experiments into feasible programs.

In general, the majority of testing to be performed in the S20 facility will not require substantial advances in testing know-how. However, the large size of the test articles will present new challenges to design economical test setups that will accomplish the test. A substantial engineering effort will be required to design the test setups. Test engineering considerations will have to be recognized in the initial design of the vehicle, and in some instances, provisions for testing must be integrated in the design. For research vehicle programs, test engineering for structural ground tests will account for as much as 10-15 percent of the total engineering effort, not including testing of the propulsion system.

Engineering efforts will be required to study the significance and value of each type of test that may be contemplated on each particular vehicle configuration. Some tests may be of very little value on some designs, while the same test may be vital to other designs.

Other than the immense size of the major section test specimens, no unusual operational problems are anticipated for room temperature structural tests and dynamic vibration tests. These types of testing will merely require the scaling up of conventional testing techniques. Although thermal testing will be performed with present-day equipment, the larger size of the test articles will increase the difficulty and risk of a successful test by several orders of magnitude.

The total amount of power that will be used in the thermal testing of a major section is approximately 10 times more than the largest heat test ever run. When attempting to control a 430 MW load on a low inductive circuit such as resistance heaters, precautions must be taken to insure that the load can be dumped to some type of power absorbing rheostat to prevent the generator from shorting out. The control must be fully automatic and computer controlled such that instant control can be exercised over each individual channel to prevent catastropic failure from occurring to the entire test system.

Instrumentation technology will require significant research to develop economical and reliable methods for measuring temperature and high temperature strain. Present-day thermocouple technology is sufficient to reliably measure temperatures up to 3000°F (1650°C) but the expense of each thermocouple installation makes a large number of thermocouples prohibitive. Present-day high temperature strain measurement technology cannot reliably measure static strains at temperatures above 600°F 600°F (312°C). A significant amount of research must be expended to gain reliable strain measuring techniques at anticipated test temperatures for hypersonic vehicle research.

Altitude testing will present new problems that were not experienced in previous space simulation testing. The rate of climb of the vehicle on a maximum-rate-of-climb trajectory must be simulated because improper venting of interior cavities can cause structural failure due to differential pressure loading. Heating tests over large areas must be performed while at cruise altitude because in many instances, the thermal protection insulation and radiation systems will only function at reduced pressure environments. Fuel flow may also be required for thermal altitude tests because the fuel mass is used in many vehicle concepts as a heat sink. If cryogenic fuel flow is required in the chamber, a remote site will be required that was not anticipated in the facility design.

A significant development effort to provide safe test procedures will be required for the operation of the hazardous remote site. Test procedures must be developed that will allow heated specimens to be tested under cryogenic fuel flow. Testing of cryogenic heat exchangers under high heat flux condition has never been done on a scale as large as anticipated in this program, and many unknowns exist in testing procedure.

The fuel slosh test track will present many operational testing problems. A substantial design effort will be required to design a sled that will enable various tank configurations to be tested. The incorporation of a vibration exciter in the sled will require development because the power for the exciter must be stored on the sled. The high current requirements of electro-mechanical shakers will prohibit their use. Because it is difficult to supply electrical power to a rapidly moving sled, some type of a stored energy (pneumatic) exciter must be developed for this unique test. Likewise, it will be impossible to simulate thermal environments on the tanks to study slosh effects on the thermal distribution of the tank.

8.5 ACQUISITION SCHEDULE

The schedule for acquisition of S20 is presented in Figure 8-11 and is based on the general considerations given in Section 2.8. It is seen that the facilities can be available for use in slightly more than 3 years.

The 3-1/4 year acquisition shown in Figure 8-11 appears reasonable to acquire the equipment and physical plant. However, unlike the flow facilities, the complex itself does not represent the research capability, which instead, depends on individual application of the heaters, shakers, load cells, acoustic generators, and other test equipment to specific programs. The initial facility checkout and calibration is just to determine that the power sources, steam ejectors, fuel supply, oxidizer supply, and so forth are performing as required. Actual refinement of the experimental techniques required to test a major section under combined time variant mechanical, thermal and altitude inputs will require about 3 to 5 years to develop. In all probability, the potential operational aircraft will have some progression in size, and the first aircraft will not be 300 feet (91.5 m) in length. The experimental capability and techniques can probably be increased over a time span so that when the maximum sized vehicles are encountered, the testing capability will be available. The realization of the complete capability for S20 will probably occur about 6 to 9 years from initiation of the acquisition program. S20 is unique in this respect. In gas dynamic and engine facilities, the capability is provided by the basic facility and is independent of experiments conducted in these facilities. For S20, however, the equipment is just a collection of hardware, and it is the organization of the equipment and test techniques associated with the actual experiment which provide the capability. In this respect, continued research in experimental techniques and measurement methods is vital for a structural research facility, such as S20. To summarize, the cost and schedule to assemble the complete S20 facility are:

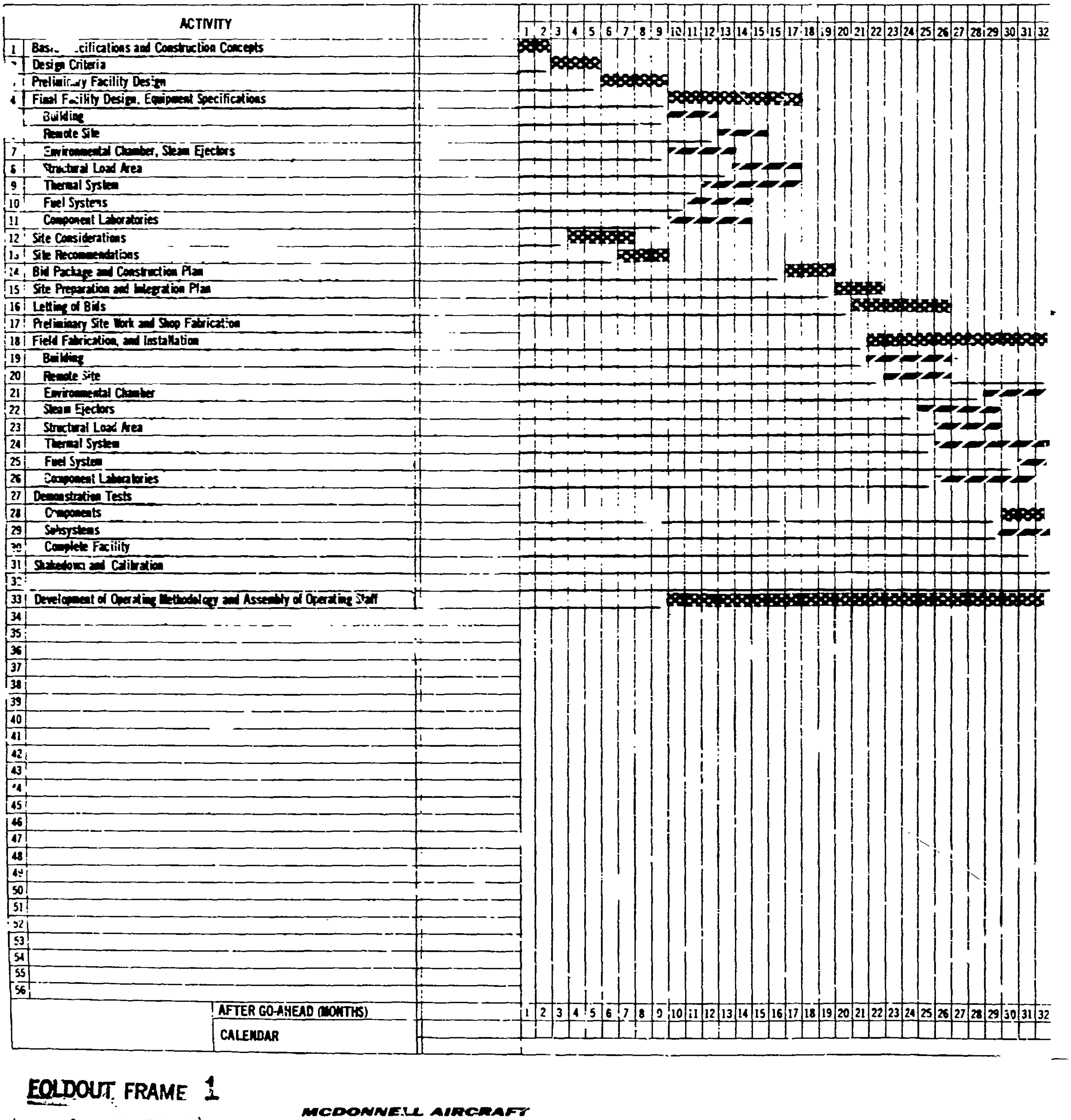
Cost - - - - - - -$237,351,000

Schedule - - - - - 39 Months

The final performance goals need not necessarily represent the initial undertaking. At the expense of increasing total costs, the annual costs could be reduced by initiating a stretched out program where the initial facility performance is less than the final goal. This requires sufficient planning so additional performance increments can be added without significant interruption of the basic facility operation.

The structures research facility has a large number of options available with respect to rate of acquisition. As was done by NASA at Cape Kennedy, where the facility capabilities for Mercury, Gemini, and Apollo were expanded as increased requirements were made known; S20 could begin at a level perhaps not differing significantly from existing capability and regarding its capability. In fact, facilities such as the NASA Langley Structures Laboratory could provide the base for the initial step. In this manner, the complete capability of handling a major section of an operational aircraft could come at the end of a ten year acquisition program, beginning with altitude/thermal/mechanical simulation capability for component sized structural elements. In this manner, the annual acquisition costs could be reduced, and the total cost of the facility probably would not be increased by more than 20%.

FIGURE 8-11
ACQUISITION SCHEDULE, STRUCTURE RESEARCH LABORATORY (S20)



FOLDOUT FRAME 1

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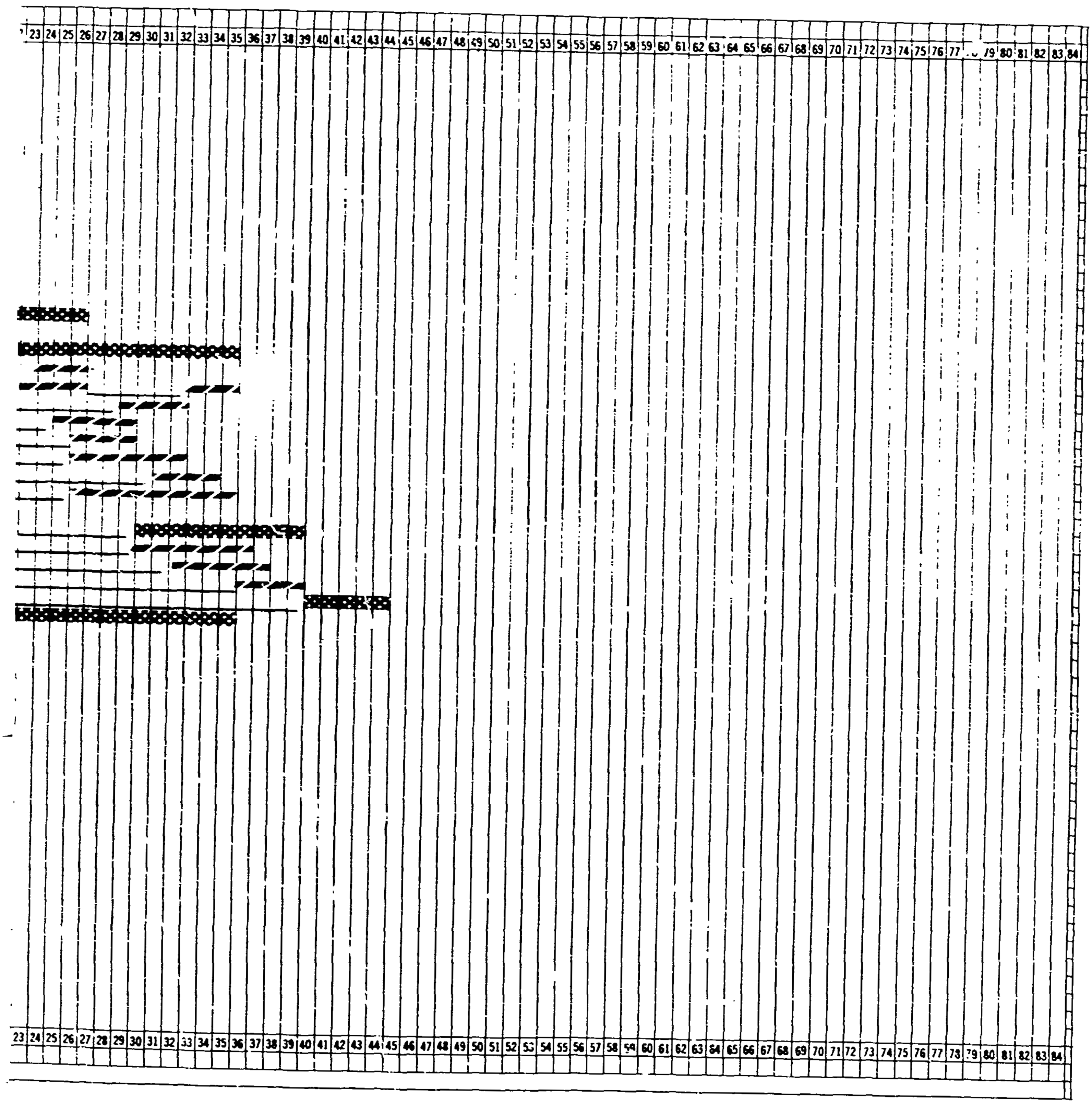

FOLDOUT FRAME 2

Postulating a possible stretched acquisition schedule the component laboratories could be first acquired for perhaps 50 million dollars, in three years. The main laboratory building and complete services could be added in another three years with full power capacity and equipment necessary for component research for another 60 million dollars. In the next two years, the test equipment could be added so that at 8 years from initial capability a major section can be tested in combined thermal/mechanical loads. In the following two years, the remote hazardous test area for testing fueled specimens, and the altitude chamber for combined altitude/thermal/mechanical tests could be installed for an additional 65 million dollars. This is 2.5 times larger than the minimum time required to acquire the facility, but the annual expenditure rate has been reduced by about 50%. The cost and schedule of this stretched acquisition schedule are then:

	Cost	Schedule
Component-Sized Testing Capability	$ 50,000,000	36 Months
Main Lab Building and Services	60,000,000	36 Months
Full-Size Structural and Thermal Test Equipment	110,000,000	24 Months
Hazardous Test Area and Altitude Chamber	65,000,000	24 Months
Total	$285,000,000	120 Months

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8.6 EVALUATION SUMMARY

The development of a hypersonic airframe that will repeatedly survive the hypersonic flight environment and yet remain within reasonable weight limits will require the use of unconventional materials and structural concepts. Some of the structural concepts and materials will be taken from existing technology, but many will evolve from research conducted to solve specific hypersonic vehicle technology probl In either case, the concepts will not have been proven to provide a reaso... ..e level of confidence for a operational system. In order to gain the required confidence to commit a vehicle design to prototype production, significant structural research must be conducted. The prototype design must then be verified by repeatedly subjecting the structure to flight environmental and loading conditions in structural ground research facilities. The scope of the ground structural research to be performed is outlined in Figure 8-12.

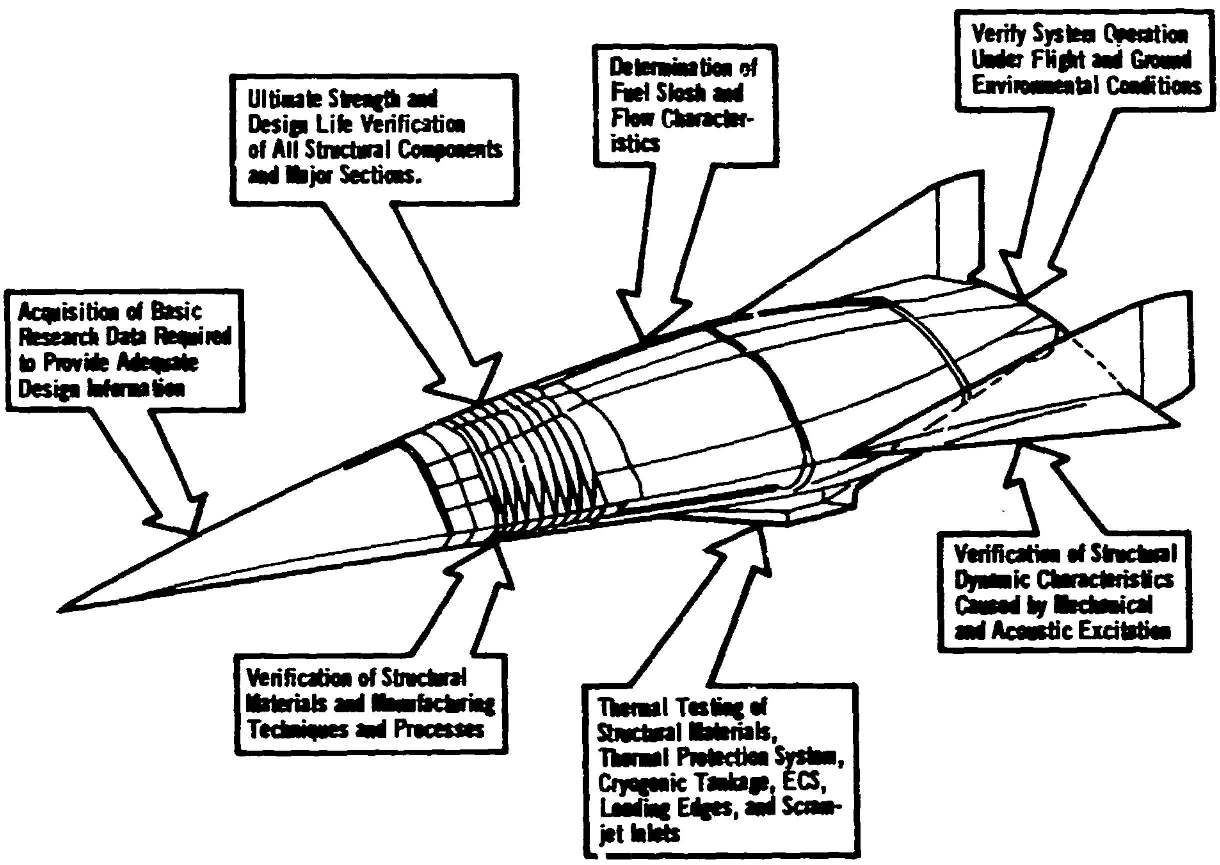
The S20 Structural Research Facility can provide realistic test environments which will subject the various thermostructural concepts to flight conditions. The maximum possible levels of confidence can be obtained in a facility similar to S20.

To provide the most beneficial and cost effective structural ground test facilities, critical environmental and loading conditions must be applied to representative test specimens. The cost of the facility is governed by the number of environments simulated and the size of the test articles. The proposed facility was chosen such that flight environments could be applied to test specimens as large as full-scale operational vehicles.

The definitions of test article size were based on a maximum sized vehicle 325 ft (98.5 m) long with a 125 ft (38 m) span. In practice, however, the initial aircraft sizes may not be that large, so that the actual equipment requirements will probably increase with time, beginning at a level of one-half to one-fourth of the maximum specified. This means that in all probability, S20 will go through a period of growth, re..lizing its complete capability only when aircraft of that maximum size are under consideration for actual acquisition.

Hard decisions still must be made with respect to the best testing philosophy for a particular airframe design. The S20 facility was intended to be a general facility that could test any of the proposed operational vehicles. Obviously, if the actual vehicle is significantly different from the baseline test article, or if the size of the test articles required are varied, the capability requirements of the ground test facility will have to be altered. For example, significant differences exist between the structural concept required for a hypersonic vehicle and a space shuttle. These structural differences will require different structural test facilities for the shuttle and hypersonic vehicle. The shuttle will fly a high angle-of-attack entry trajectory that results in high lift and drag and increases the altitude at which deceleration occurs. This in turn shortens the duration of the heat pulse on the vehicle. Since high angle-of-attack flight trajectories expose only the lower body and wing surfaces and leading edges to significant heating, many areas of the structure will not require extensive thermal protection. Due to the high altitude/high angle-of-attack trajectory, the shuttle structure will be subjected to much lower dynamic pressure and wing loadings than

FIGURE 8–12
SCOPE OF NON-FLOW GROUND TESTING



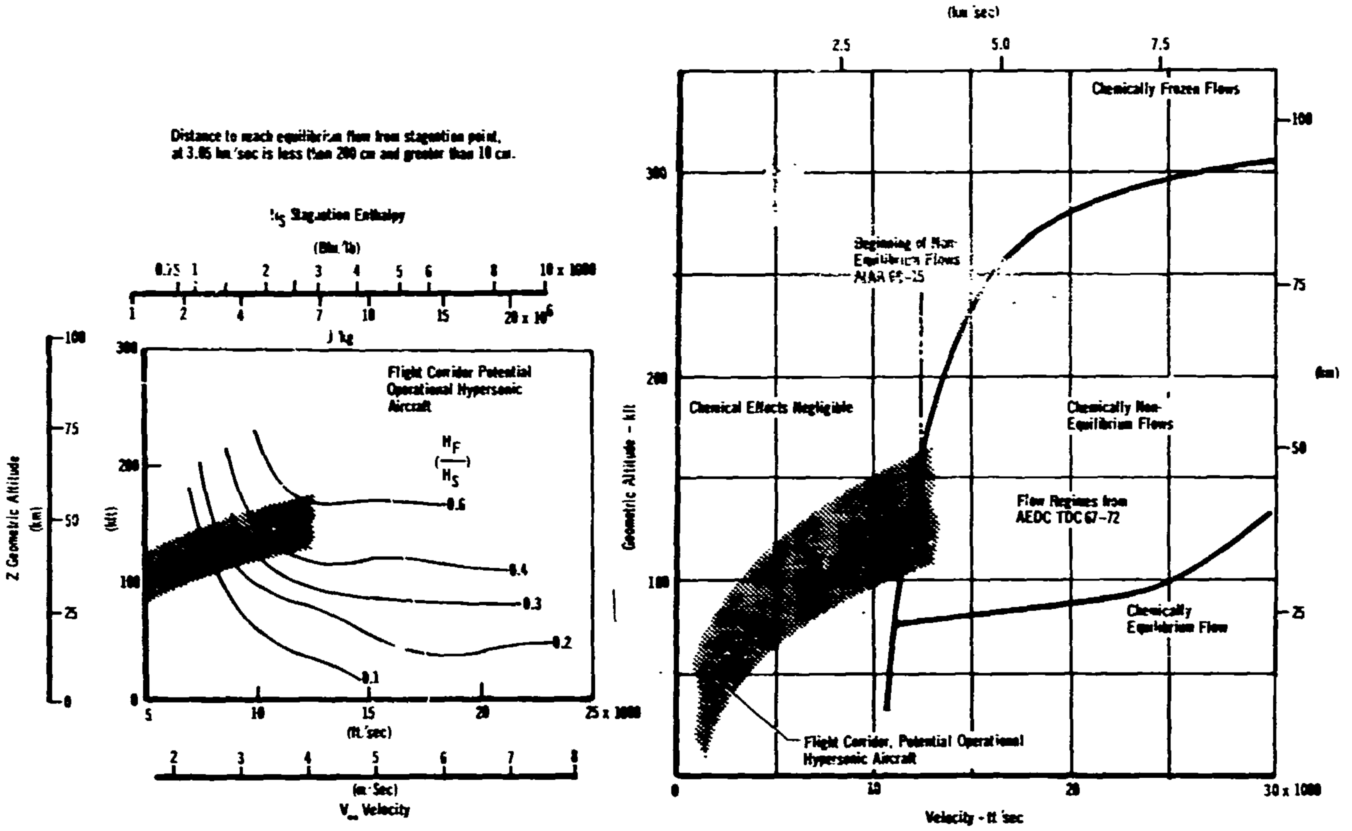
will be experienced by a typical hypersonic aircraft. The maximum dynamic pressure experienced by a hypersonic vehicle could exceed 2000 psf (95,700 N/m^2), where a typical shuttle trajectory will only produce a maximum dynamic load of 50 psf (2390 N/m^2). The maximum leading edge temperature for the shuttle is expected to be less than 2200°F (1215°C), where leading edge temperature for the hypersonic trajectory will exceed 3000°F (1647°C).

An additional consideration for structural research was the capability to provide a flow environment to evaluate material/structural systems under flight duplicated aerodynamic conditions in addition to the normal structural non-flow capability. The only group of facilities providing flight duplicated conditions were the engine research facilities. The engine facilities were therefore provided with the capability of accommodating aerodynamic nozzles to generate a testing medium where flight velocity, Mach number, and altitude were duplicated. Although the effects of gas chemical kinetics in the overall flow around the aircraft will be negligible for Mach numbers of 12 or less, there are regions of local non-equilibrium flow in the vicinity of leading edges, and noses, as shown in Figure 8-13. Regions near the leading edges therefore could have fractions of the total energy contained in frozen atom concentrations during the expansion process around the leading edges. This could mean that if the wall chemical characteristics were such as to enhance atom recombination at the wall, more energy than predicted by equilibrium theory may be transferred to the wall, increasing leading edge temperature. On the other hand, it is just as possible, for coated refractory metals, that the atom recombination rate at the wall may be impeded thus reducing heat transfer rates and surface temperatures. Whether or not this alteration of the wall/gas chemistry actually is of the magnitude predicted by theory (Ref. 11 and 12) must be verified by using the actual material, in the shape and construction envisioned for an actual aircraft, exposed to an air flow which duplicates local flow conditions. These factors should make the addition of the aerodynamic nozzles a significant improvement to the overall thermal/structural research capability for determining actu l air/materials interactions.

During Phase III, a final list of 278 Research Tasks, each task being a subset of the 78 Research Objectives, was defined. This list of research tasks was used to determine the research potential of each candidate research facility considered during Phase III. Details of this analysis and evaluation are contained in Volume IV, Part 3.

S20 is identified with a limited number of Research Objectives compared to some of the flow facilities. It does, however, accomplish a high percentage of the applicable research objective tasks. The capability of S20 to provide high temperature structural environments means its applicability is not limited to HYFAC type aircraft alone. The following matrix is representative of the diverse capability of S20.

FIGURE 8-13
CHEMICAL KINETIC CONSIDERATIONS



Increased Research Capability in the Area of	HYFAC	SPACE TRANS-PORTATION SYSTEM	SPACECRAFT	STRATEGIC/TACTICAL MISSILES
Material Research	o	o	o	X*
Structural Qualification	o	o	o	o
Fatigue Research	o	o	o	
Materials System Limitations	o	o	o	o*
Theory Verification	o	o	o	o
Thermal Modeling	o	o	o	o
Fluid System Research	o	o	o	
Horizontal Tank Dynamics	o	o		
Cryogenic Fuel Stability	o	o	o	

Contribution

o significant
X limited

*ablation thermal protection systems would be limited to providing input heat and bulk material temperature

The numerical value of 4.5 for the facility confidence level indicates the low risk involved in acquiring the S20 facility complex. Not indicated is the uncertainty associated with assembling the hardware into a complete structural program. It is very difficult, for example, to use half a wind tunnel test section, but it is indeed possible to use less than the total number of heaters, load cells, shakers on a multi-million dollar structure specimen. The actual test program may require less dollar outlay than the cost of the specimen itself. A total time period for a test of this magnitude may be 2 to 3 years from beginning of installation to removal of the structure specimen. The total cost for S20 of about 131 million dollars appears consistent with the tenfold increase in thermal heating capability over existing facilities that it provides. Considering that the maximum sized aircraft will be somewhat later in the aircraft development cycle, a minimum yearly acquisition cost program could be followed where the minimum 3-1/4 year acquisition schedule is stretched out over a ten year period, gradually increasing capability.

The success of any hypersonic vehicle program will depend on the materials, design concepts, and technology base the program is premised on. Undoubtedly, the development of a practical re-usable thermostructural concept will be one of the primary cornerstones upon which the success of the program will stand or fall. The development of a successful thermostructural system will be directly affected by the availability of adequate test facilities. Without the proper ground test facilities, the desired confidence levels will not be achieved, thereby committing the design to production or flight with an undesirable degree of risk.

9. COMMERCIAL INDUSTRY SUPPLIED DATA

In determining the present maximum capabilities of equipment utilized in the operation of the candidate ground research facilities, a significant contribution was made to this study by the manufacturers, suppliers, and users of the various equipment categories. The equipment requirements specified by the size and research capability of the candidate ground research facilities was such taht without these firms' gratis contributions, the confidence in the technical assessments and cost would have diminished. The firms which contributed were:

Ingersol-Rand New York, N. Y.	Conventional steam ejector design and costs.
Pratt-Whitney East Hartford, Connecticut	Industrial gas turbine generating systems and costs.
General Electric Cleveland, Ohio Evendale, Ohio	Industrial gas turbines and ground applications of advanced aircraft turbines. Gas/steam turbine compound generating system packages.
Allis Chalmers Milwaukee, Wisconsin	Compressor plant design and specifications. Costs of large, high pressure control values.
Combustion Engineering Windson, Connecticut	Conventional ejectors
Cabot Corporation Boston, Massachusetts	Carbon monoxide and carbon combustion systems, technical and cost data.
F. C. Brown New York, New York	Chemically fueled steam generators and ejectors.
Niagara-Mohawk Power Co. Buffalo, New York	Power availability, rate structures, considerations involved in establishing user rates, facility operational characteristics with respect to network stability.
Union Electric Company St. Louis, Missouri	Commercial power rates and information regarding the pumped storage facility at Taum Sauk.
City Light & Power Company Jacksonville, Illinois	Practical advice concerning costs and operation of packaged gas turbine generating units.
McDonnell Douglas Astronautics Co. Huntington Beach, California	Muffler design and enforced community noise standards.

Cleveland Coppersmith Company Cleveland, Ohio	Design fabrication and cost information on water cooled induction coils.
Ajax Magnethermic Company Cleveland, Ohic	Design fabrication and cost information on water cooled induction coils.
Coen Company Burlinsame, California	Oil fired combustion heat exchanger costs.
Nooter Corporation St. Louis, Missouri	Pressure vessel fabrication technology and costs.
Norton Company Worchester, Massachusetts	Zirconia properties, commercially available shapes, material & fabrication costs.
Fansteel Corporation North Chicago, Illinois	Refractory metal properties, costs, and fabrication problems.
P. D. M. Steel Company Pittsburgh, Pennsylvania	High pressure control valves.
Vilter Manufacturing Company Milwaukee, Wisconsin	Technical and cost estimates for mechanical refrigeration plants and water cooling systems.
Air Reduction Company New York, New York	Costs of cryogenic fluids.
Process and Chemical Equipment Co. St. Louis, Missouri	Control valves and piping estimates.
Cleaver, Brooks Company Milwaukee, Wisconsin	Conventional boiler costs.
Arnold Engineering Development Center Tullahoma, Tennessee	Cored brick heater design & performance design details, hypersonic 2-D nozzle fabrication consideration, 16S & T nozzles, operation and maintenance costs of compressor plants. Utilization rates of major facilities. Proposed facility performance goals and specifications. TVA power utilization & costs.
NASA Lewis Research Center, Plumbrook Cleveland, Ohio	Technical details of the electric induction heater as applied to a flow facility.
NASA Langley Research Center Aerophysics Branch Hampton, Virginia	Minimum Reynolds number simulation requirements. Scramjet testing requirements high temperature Arc heater concept.

Naval Ordnance Laboratory Silver Spring, White Oak, Maryland	Operating details and problems concerning the gas piston driver concept

10. ASSESSMENT AND RECOMMENDATIONS - SUMMARY

The five ground research facilities refined in Phase III represent the facilities required to accomplish the research specified in the Research Objectives that could not be accomplished in existing facilities. In terms of the research applicable to future high performance aircraft, probably the most pressing need is in the areas of engine and structural research. This is not to imply that aerothermodynamic research capability does not require improvements, but rather suggests the dominating influence that both engine performance, size, and weight and structural strength and weight have on the final aerodynamic configuration. The turbomachinery engine facility represents the longest term development and acquisition program, and could affect the acquisition of other research facilities. A program which anticipated acquiring all of the candidate research facilities would in reality probably be extended over a ten to twelve year acquisition program, necessitating establishing some priority of acquisition. Some considerations which went into determining the schedules and the alternatives are discussed in this section.

10.1 COST AND SCHEDULES

The five facility concepts refined in Phase III represent definition of a performance goal based on the research requirements defined in the Research Objectives. Although primarily consisting of components based on existing technology, these facilities will require a period of performance development, after initial operation, where the operations of the numerous subsystems are better interfaced to achieve the maximum performance. Except for specific items associated with the engine research facilities, the development assessment for the overall facilities is quite favorable. It would appear that any of the five ground research facilities could be built (although with varying degrees of difficulty) and possesses a good to excellent chance of achieving its desired goals. For some facilities the final performance goals need not necessarily represent the initial undertaking. At the expense of increasing total costs, the annual costs could be reduced by initiating a stretched out program where the initial facility performance is less than the final goal. Sufficient planning must be done so that additional performance increments can be added without significant interruption of the basic facility operation. The potential of reduced initial acquisition costs is different for each candidate ground research facility. Various aspects of these alternatives for the individual candidate ground research facilities have been previously discussed. Figure 10-1 summarizes a postulated acquisition schedule and shows the required annual cash flow and cumulative expenditures based on this schedule. The postulated schedule has been worked out so that the complete capability would be available in 10 to 12 years and so that annual cash flow is less than that required if all facilities were started simultaneously at their ultimate performance potential. It can be seen that the total annual cash flow ranges from a minimum of $12.7 million during the first year of the program to a high of $158 million during the eighth year. The cumulative expenditures for the postulated program would be about $1.014 billion, compared to the basic cost of $940 million obtained by constructing each facility with its ultimate performance at the outset. This postulated schedule is only one of many possible arrangements and is presented to give a quantitative idea of the costs involved in such a program and of the time required to obtain the desired research capability for hypersonic aircraft and engines.

Some of th[illegible] [illegible]ruction schedule and cost alternatives have been discussed previously for [illegible] [illegible]cility. The foll[illegible]ng discussion presents the alternate which has been chosen for the postulated composite schedule for each facility.

(1) The hypersonic test leg of GD20 is constructed after the trisonic test leg. The complete building for the compressor plant can be initially constructed to accommodate the final number of machines. Since the compressors for the hypersonic leg require a portion of the output from the compressors for the trisonic leg; provisions should be provided to add these compressors at a later date without seriously interrupting the operation of the trisonic leg. Adding the hypersonic test leg at a later time reduces the initial acquisition cost by the amount required for the air compressor, valves, test leg, muffler and air storage tanks. Since a common control room and data acquisition system building are envisioned, it is assumed this would be built in nearly final form.

(2) The cost of the GD7 hypersonic research facility is so low compared to the total program cost that no significant cash flow reduction is obtained by a program stretch-out. It was therefore decided to design and construct both test legs simultaneously to the ultimate specifications. Program initiation need not start until the 5th year of the over-all program start since only five years are required for completion.

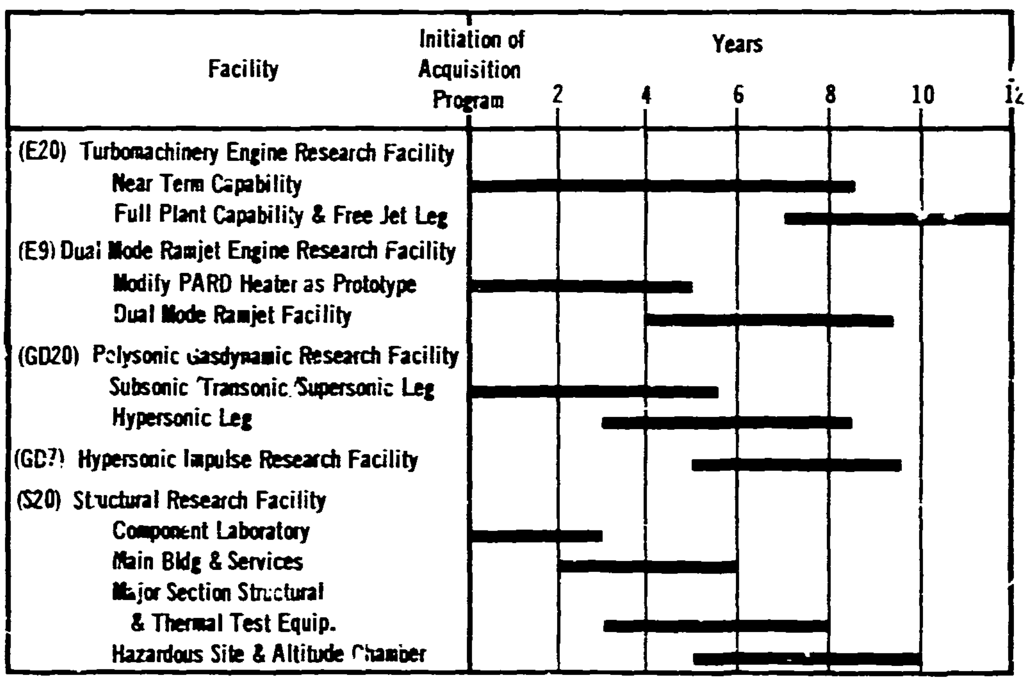
(3) The initial performance of E20 will accommodate direct connect testing of near-term engines, with the full performance added later when the requirements materialize. Based on mass flows for current study engines, the compressor mass flow can be reduced some [illegible] the induction heaters deferred and the refrigeration plant sized for turbojets [illegible] turbofans, without compromising the research capability in terms of the nearer term engines. This reduced capability can provide flight duplicated conditions to Mach 3.8. The preliminary design must be capable of expansion to the full ultimate facility specifications. The schedule would not be changed significantly because other pacing items such as cooler, heaters, and so forth are still necessary. The additional compressor capability could probably be provided in a 34 to 38 month period at some later time. The alternative of not immediately providing either the induction heaters or the free jet test leg provides additional time for reduced scale development of these two high risk components at the same time that the basic facility is being checked out and put into routine operation. Time is also available in the case that planned approaches to these two items do not bear fruit and alternative concepts have to be developed.

(4) In the postulated schedule, E9 is constructed at its full capability, with initial design starting in the fourth year of the over-all program. A five year program of prototype development is proposed, wherein an existing blowdown pebble bed facility (such as the PARD heater at Langley) is equipped with a carbon combustor and a scramjet test section. This development work must be done prior to actual design of the E9 facility in order to solve the operational and materials problems to be expected with these components.

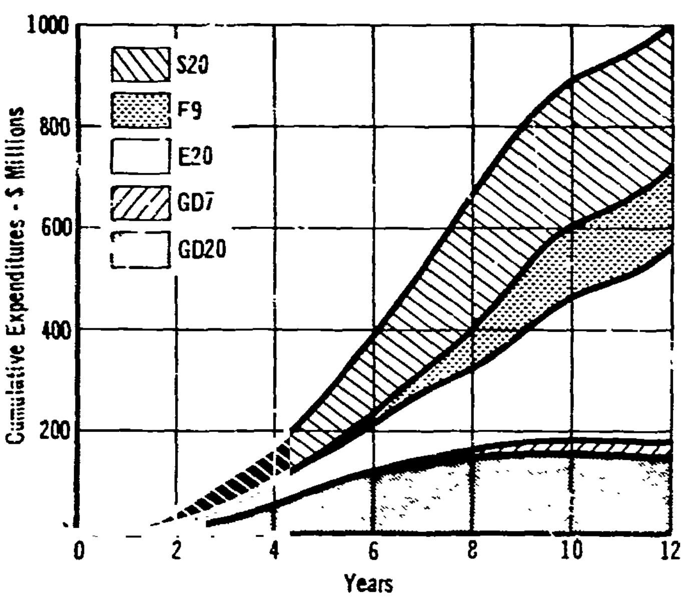
(5) The structural research facility is best constructed in incremental stages. The component laboratories could be acquired in three years for perhaps 50 million dollars. The main laboratory building and complete services could be added in another three years with full power capacity and equipment necessary for component research for another 60 million dollars. In the next two years, the test equipment

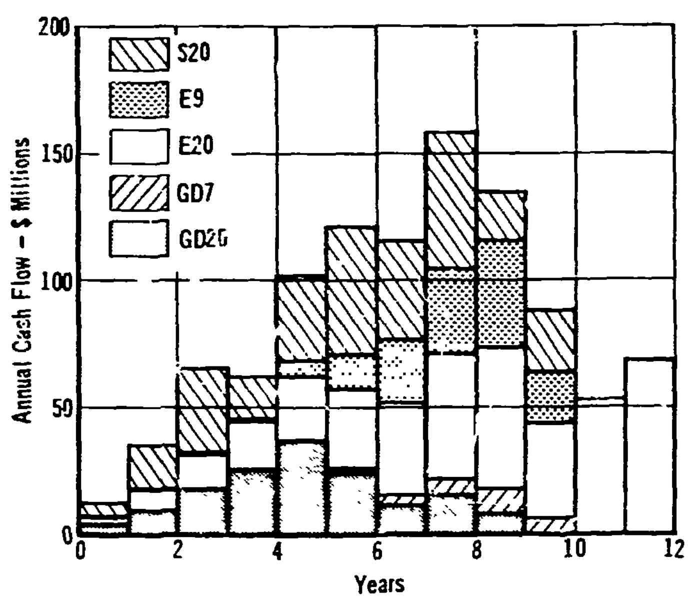
FIGURE 10-1
POSTULATED COMPOSITE SCHEDULE FOR INCREMENTAL ACQUISITION

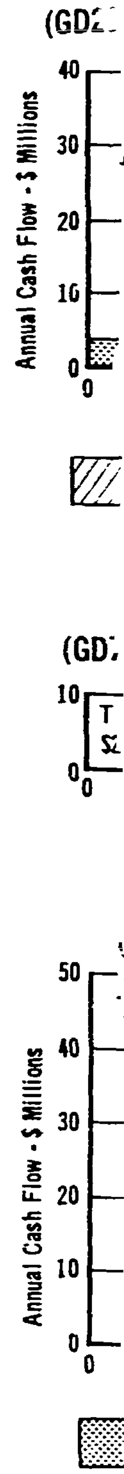
Composite Schedule, Cash Flow, and Cumulative Expenditures



COST DISTRIBUTIONS FOR ALL FACILITIES



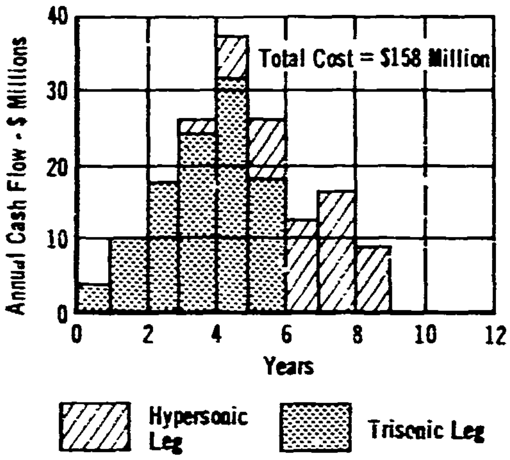




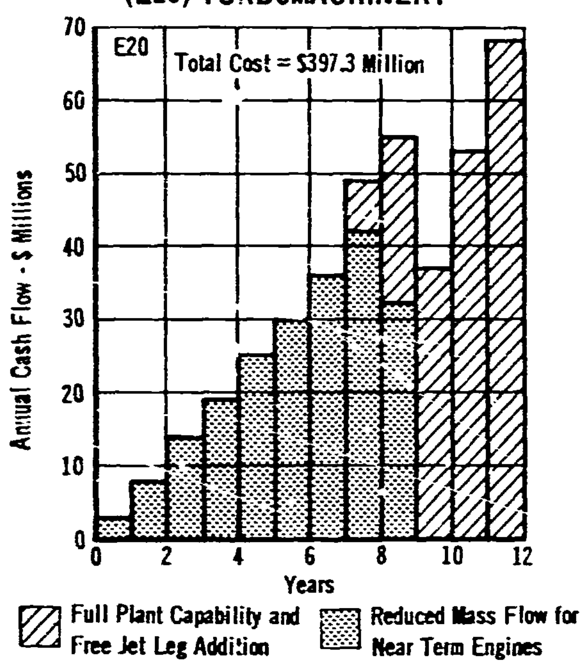
FOLDOUT FRAME 1

ANNUAL CASH FLOW - INDIVIDUAL FACILITIES

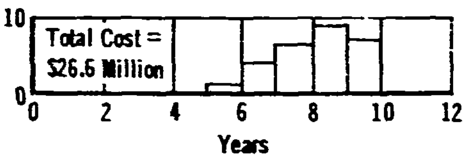
(GD20) POLYSONIC WIND TUNNEL



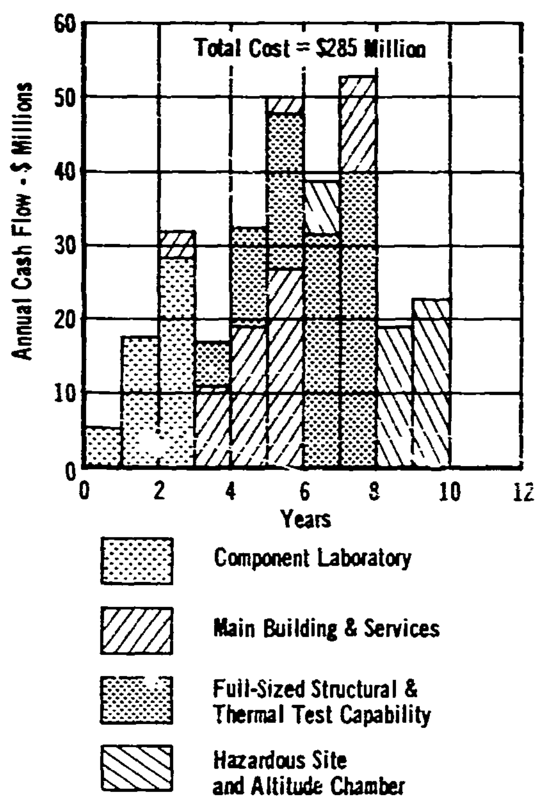
(E20) TURBOMACHINERY



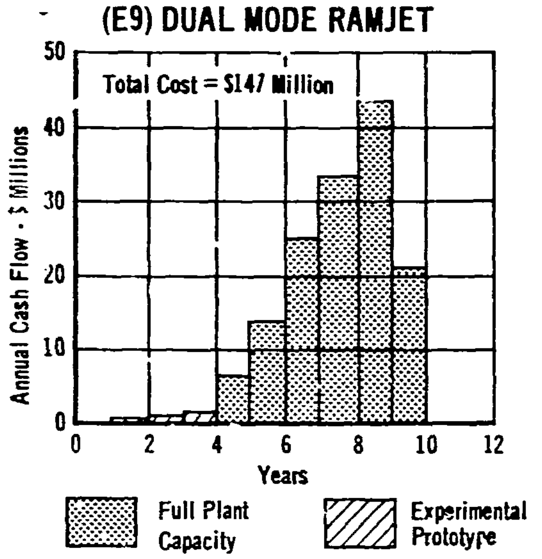
(GD7) HYPERSONIC WIND TUNNEL



(S20) STRUCTURES TEST



(E9) DUAL MODE RAMJET



could be tested in combined thermal/mechanical loads. In the following two years, the remote hazardous test area for testing fueled specimens, and the altitude chamber for combined altitude/thermal/mechanical tests could be installed for an additional 65 million dollars. This is 2.5 times longer than the minimum time required to acquire the facility, but the annual expenditure rate has been reduced by about 50%.

10.2 RECOMMENDATIONS

Considering the existence of well over a thousand wind tunnel, engine, structures, materials, and hardware oriented experimental facilities in government, industry, and university organizations which contribute to aeronautical technology, the fact that the five ground research facilities refined in Phase III were judged as capable of increasing the research potential by fifty percent speaks for the magnitude of these five proposed facilities.

In terms of general application, GD20 appears to offer significant research capability improvements for a wide range of aeronautical applications from transport to hypersonic launch vehicles. This particular facility would represent an additional degree of flexibility in that the same models and test section cart used for high Reynolds number work would be interchangeable with the 16 foot (4.9 m) AEDC propulsion tunnels where additional research on engine integration could be accomplished. Major multi-billion dollar programs such as the Boeing 747, Lockheed 1011, McDonnell Douglas DC-10, and Lockheed C5A, requiring Reynolds numbers simulation well in excess of current capability, have been committed by private industry with a relative success. Therefore, although GD20 would indeed be desirable as an additional research tool, its acquisition is probably dependent on the acquisition of a large hypersonic airbreathing aircraft.

GD7, although relatively inexpensive in comparison to the other study facilities, is a very desirable facility in terms of its high Reynolds number capability in its Mach number range. Existing facilities in this range suffer from lack of size, low unit Reynolds numbers, and/or short run times. The superior specifications of GD7 in these areas, plus its low operating cost which derives from its impulse type of operation combined with its relatively long run time, lead to its recommendation for acquisition.

E20 is predicated on the development of advanced composite engines with high supersonic capability. If considered in its proposed initial step of duplicated Mach number to 3.8, it is really an upgraded Large Engine Test Facility (LETF) as proposed by AEDC. In fact, an additional 40 to 50 million dollar investment to LETF would provide the mass flow and temperature capability represented by this initial step for E20. The final step for E20, going up to Mach 5.5 duplicated flight conditions, would be costly, and offers the highest risk associated with attaining the performance goals of E20. Such an investment would only be required if large engines in this Mach number class were actually going to be developed.

E9 is a large facility of unique capabilities, combining pure air performance testing on a blowdown basis with vitiated air testing, for thermal conditioning of

PRECEDING PAGE BLANK NOT FILMED

engine modules and PFRT testing, on a continuous basis. It can greatly increase CSJ and SJ development progress, permitting much of the engine development work to be done on the ground and decreasing the dependence on flight test results.

As mentioned previously, the facility development testing of the carbon combustor and scramjet module concepts are required prior to commitment to design. Such testing is possible in a variety of existing pebble bed blowdown facilities.

The major facility for scramjet testing now in advanced planning is the True Temperature Tunnel (TRIPLETEE) at AEDC, which is a vary large pebble bed blowdown free jet facility. It is possible, having proved the unique concepts of E9 on a small prototype, to incorporate the carbon combustor, additional compressor plant capacity, and the scramjet module test section into a TRIPLETEE facility at an additional cost of about 80% of the basic E9 costs.

If subsequent research reveals an imperative need for pure air testing, a multirecompression heater, either continuous or intermittent, could be added to the facility, but at a very high cost and technical risk (Section 7.2.6).

As discussed in Section 10.1, S20 could be acquired over a long period of time, with gradual increases in performance. In this respect it represents the most likely candidate for an early acquisition. Moderate initial investments could provide a research capability in materials and structures in excess of current capability, and the basis for substantial growth in future years.

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APPENDIX A

The location of even moderately sized wind tunnels near populated, incorporated areas can impose significant restrictions. Presented in this appendix is an excerpt from Resolution Number 231, entitled, "A Resolution of the City Planning Commission of the City of El Segundo, California, Recommending the Establishment of a Wind Tunnel by Douglas Aircraft Company, Inc., within a Certain Specified Area and Under Certain Conditions". Specifically this resolution specifies the acceptable noise level which the City of El Segundo required Douglas to demonstrate before routine facility operation would be permitted. Douglas Aircraft Company (a divisional company of the McDonnell Douglas Corporation) supplied the specifications and plans of a muffler system used on their 4 x 4 ft (1.2 x 1.2 m) trisonic facility which met the requirements specified in the subject resolution. This was used as the basis of the muffler design for the HYFAC ground research facilities and was scaled on a mass flow per unit area basis. In order to indicate the stringency of the requirements a large office can easily have a sound level equivalent to 70 to 80 dB. The excerpt from Resolution Number 231 follows, beginning with page F of the resolution.

THEREFORE BE IT RESOLVED FURTHER, that the Planning Commission recommends the approval of the application of the Douglas Aircraft Company, Inc. for the construction, and operation of wind tunnels, one of which will approximately be the size as that permitted under the application of North American Aviation, Inc., and the other approximately one-third the size of the larger one to be used for testing smaller devices, thus giving more flexibility to the operation, both to be established on the following described property.

> The West 630 feet of the North 741.43 feet of the Northeast Quarter of the Northeast Quarter of Section 18, Township 3, Range 14W, Rancho Sausal Redondo in the City of El Segundo, County of Los Angeles, State of California, except the North 50 feet thereof which is dedicated for road purposes.

and shall be subject to the identical controls, limitations and performance standards made applicable in the previous case, to wit:

1. For the purposes of convenience in reference and in determining the boundaries of the area above described, there shall be attached hereto and designated as "Exhibit A" a map or plat entitled "Trisonic Wind Tunnel Site Proposals 3 & 4 El Segundo. Said Exhibit A is hereby referred to and by this reference incorporated herein and made a part hereof.

2. Prior to the completion of the wind tunnels, the Douglas Aircraft Company, Inc. shall submit to the City Council of El Segundo a statement in writing by a recognized acoustical expert employed by the Douglas Aircraft Company, Inc., to the effect that the wind tunnel has been designed to achieve noise levels at one-half mile not greater than the following:

Frequency Bands Cps	Sound Pressure Levels dB re 0.0002 microbar
20-75	72
75-150	61
150-300	53
300-600	48
600-1200	44
1200-2400	41
2400-4800	39
4800-10,000	37

3. That the construction, operation and maintenance of the said wind tunnels and their appurtenances shall be such that the actual noise levels one-half mile from the site when measured in accordance with "4" below, shall in any one frequency band, averaged over the 12 positions specified, not exceed the numbers tabulated above by more than 10 db for operation between the hours of 7:00 o'clock A.M. to 10:00 o'clock P.M., nor more than 5 db for operation between the hours of 10:00 o'clock P.M. and 7:00 o'clock A.M.

4. The noise measuring equipment used for determining the actual noise levels shall consist of a Sound Level Meter meeting the specifications contained in "American Standards on Sound Level Meters Z 24.3 (1944)" and an Octave Band Analyzer meeting the specifications contained in "American Standards on Octave-Band Filter Sets Z 24.10 (1953)" and the equipment shall be in proper calibration at the time of performance of the tests.

The average noise levels shall be determined from octave-band noise level measures made at not less than 12 positions equally distant from each other at a distance of one-half mile from the site and so arranged as to completely encircle the site.

In order that any test in any octave band be considered valid, the background noise level in each octave band with the tunnel not in operation shall be at least 6 db below any reading in that octave band taken with the tunnel in operation.

The weighting network of the sound level meter shall be in the "C" position; the meter speed on the octave band analyzer shall be in the "slow" position; readings shall be taken at the steadiest position of the indicating needle during the 30-second period of operation of the tunnel or at the peak positions if the noise is of a pulsating nature; the microphone should be supported on a microphone stand about 4 feet high; the sound shall impinge upon the diaphragm of the microphone at grazing incidence; all necessary microphone response, cable and temperature corrections shall be applied to the finally tabulated data; and the measurements must be performed only if the wind speed is less than 5 miles per hour.

and

FINALLY RESOLVED, that a copy of this Resolution shall be forwarded to the City Council for its action as required by law.

Passed, approved and adopted this 28th day of November, 1955.

George E. Binder

Secretary of the City Planning
Commission of the City of
El Segundo, California

William G. Thompson

Chairman pro tem of the City Planning
Commission of the City of
El Segundo, California